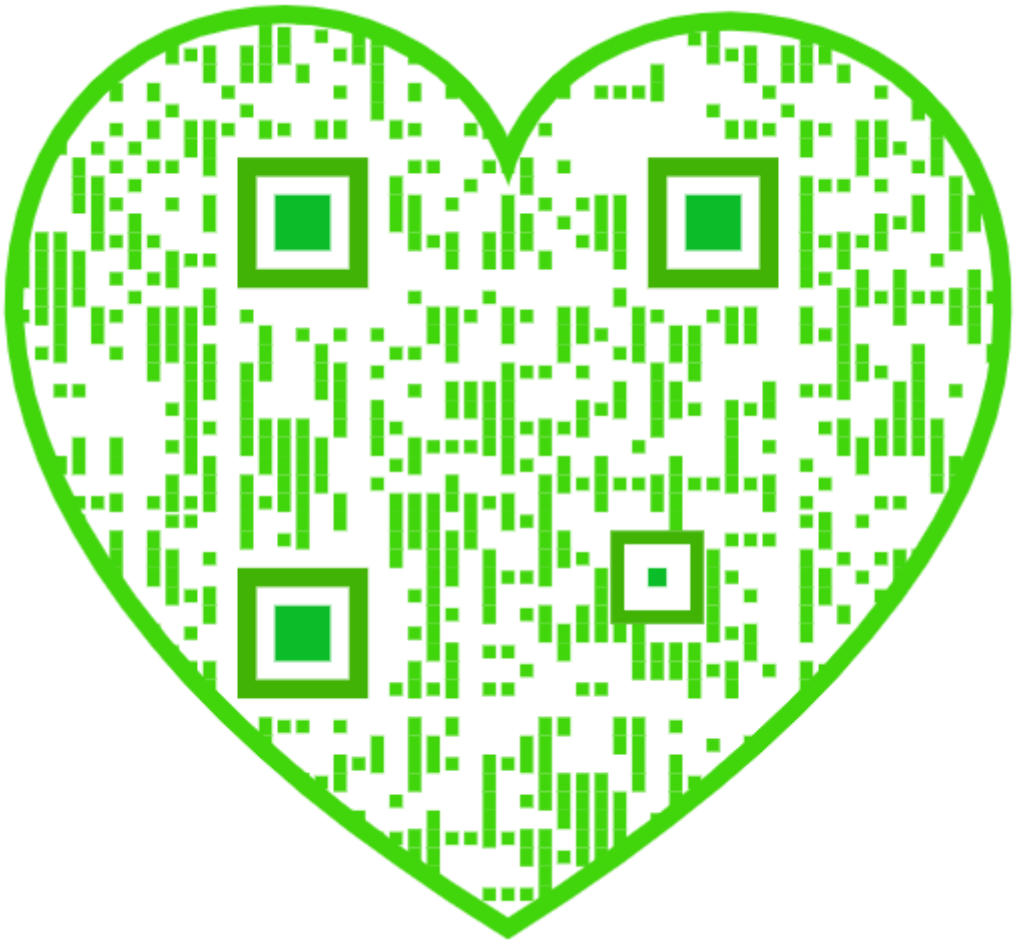

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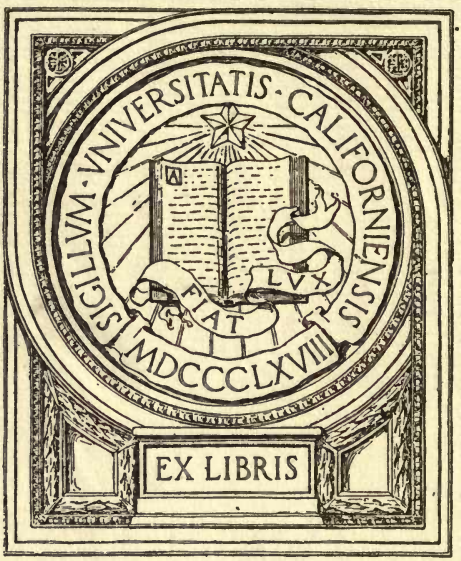

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THE

MANUFACTURE OF OPTICAL GLASS AND OF OPTICAL SYSTEMS

A WAR-TIME PROBLEM

May, 1921

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WAR DEPARTMENT,
OFFICE OF THE CHIEF OF ORDNANCE,
January 3, 1921.

This work on the Manufacture of Optical Glass and of Optical Systems was prepared at the request of the artillery division of this office by Lieut. Col. F. E. Wright, Ordnance Reserve Corps. Col. Wright was in charge of production and inspection of optical glass at the plant of the Bausch & Lomb Optical Co. from April, 1917, to May, 1918; the Army representative on the military optical glass and instrument section of the War Industries Board from March 15, 1918, until after the armistice; chairman of the Army commodity committee on optical glass and instruments under the Director of Purchase, Storage and Traffic from April, 1918, until after the armistice; and in charge of optical systems in the fire-control section of the engineering division of this office from August 4, 1918, to June 16, 1919.

The treatise is approved for publication.

C. C. WILLIAMS,
Major General, Chief of Ordnance,
United States Army.

THE MANUFACTURE OF OPTICAL GLASS AND OF OPTICAL SYSTEMS.

A WAR-TIME PROBLEM

Chapter I.

INTRODUCTION.

War has been called a contest of brains and brawn. Among the ancients emphasis was placed on brawn, on individual prowess and skill; but with the passing centuries and the development of science and technology, the engineering side of warfare has gradually gained the ascendency. At the present time much of warfare is applied engineering. In the recent war Germany had in this respect a great advantage because many of its scientists and technical industrial forces had been engaged for years before the war in the design and manufacture of war matériel, whereas no efforts of like magnitude had been put forth by the allies. In certain branches of industry, moreover, the Germans had established practically a world monopoly.

In industries of a highly technical nature, such as the chemical dye industry and the optical glass and instrument industry, the Germans had established such effective control that at the beginning of the war we were seriously embarrassed because we did not manufacture these commodities, and did not know how to make them. The Germans had been at the task for more than a quarter century and had developed a personnel trained and competent for the tasks. Their best scientists and engineers had originated and followed through the factory processes and were thoroughly familiar with them; with us it was a serious question whether we would be able to accomplish anything adequate in time to be of service on the field of battle. The records show that in the short period of 19 months, we did accomplish much to overtake the decades of German experience. In certain instances, as in optical glass and instruments, there has been developed in this country an industry which more than suffices for our own needs and which will render us independent of Europe if we so desire.

What is optical glass and what is its connection with modern warfare? At the time of the Civil War it was not used to any extent and why should it now have become such a vital necessity? These

questions are best answered by a comparison of the Civil War methods of artillery warfare with those of the present time.

During the Civil War artillery was used extensively by both sides and, judged by the standards of that period, was effective and served the purpose well; but, had the same sort of artillery been employed in the recent European war, it would have been of little value, and, in many instances, a positive hindrance to the troops in the field.

The cannon of the Civil War were, for the most part, of cast iron and smooth bore, and were loaded at the muzzle. Spherical cast-iron projectiles weighing 6 pounds, 12 pounds, and up to 42 pounds, were used effectively at ranges between one-half mile and 1 mile; shrapnel or spherical case shot between 500 and 800 yards; grape and cannister shot for less distances even down to 150 yards. High-explosive and gas shells were unknown. The cannon were fired point blank at the visible enemy. Both direct and ricochet firing were employed; indirect firing against an invisible target, which plays such an important rôle in modern artillery practice, was unknown. Distances were estimated by the eye and by observing the fall of projectiles. Range-finding devices were considered to be of little value and were not employed.

The guns were pointed by means of open metal sights attached directly to the cannon barrel; the sight resembled in many respects the sights on the modern rifle. The gunner pointed the gun by looking through a peephole in the rear sight and aligning the front sight near the muzzle of the gun with the target. After having leveled the gun by a simple spirit level, obtained the line of sight and estimated the distance to the target, the gunner elevated his cannon to the proper angle, which he measured by means of a gunner's quadrant that consisted essentially of a wooden frame with plumb line and bob combined with a graduated circle, or by means of a graduated vertical bar on which the peep sight was arranged to move.

Optical instruments for the direction and control of firing were unknown in the Civil War and would have served little purpose with the ordnance then available. During the past half century, however, artillery construction and practice have developed at an unprecedented rate. The power and precision of the guns have been increased to the extent that at the present time relatively small targets may be successfully attacked at ranges up to 40,000 and 60,000 yards. Most of the firing by modern artillery is directed at objects either below the horizon or hidden by intervening obstacles and hence not visible to the gunner, but whose positions have been accurately located on the map, either by land or aerial reconnaissance. Firing under these conditions becomes an engineering problem and the method of instrumental aim known as indirect fire control is employed.

This method requires the use of surveying instruments and serves to determine the line of sight and the distance to the target with reference to fixed points that are visible to the battery. This method is used not only in firing at hidden targets located miles away, but also in laying down a barrage, or deluge of missles, in front of an advancing line of troops, thus clearing the way for them and preventing counter-attacks by the enemy.

The essential difference between the old and the new artillery practice is one of distance and degree of precision attained. At the time of the Civil War the artillery was fired point blank in the general direction of the enemy, and the effort was made to overwhelm him with shots at close range. The gunners sighted their fieldpieces hastily and banged away, trusting to hit some vital spot. Modern artillery is concerned chiefly with much longer ranges and the aiming must be accurate, otherwise the target is missed altogether. This degree of accuracy is attainable only by means of optical instruments of high precision which serve both as observational instruments for detecting details of distant objects, noting the accuracy of the firing, and as surveying instruments for measuring angles correctly. These instruments are not only exact but also sufficiently rugged to withstand the violent concussion of rapid artillery fire. The French 75-millimeter gun, for example, which proved so effective in the late war, has a range of 8,300 yards, and can be fired at the rate of 30 shots per minute, as against the 2 shots per minute of the Civil War. The gun, moreover, is an instrument of high precision and the shots can be placed by the gunner practically where he wants them. The best breech-loading musket rifle in Civil War days could be fired 10 times per minute as against 600 shots per minute by a modern machine gun.

The gunner of to-day who is not equipped with proper fire-control apparatus is almost helpless in the presence of the enemy; he can not see to aim properly without these aids and his firing serves little purpose. The effectiveness of modern artillery and, with it, that of the active army in the field, depends to a large extent on the quality and the quantity of its fire-control equipment. This is only one of a number of the fundamental requisites of the complex army of to-day. Yesterday many of the essentials of to-day were unknown; and yet, when war comes upon us, we can not fight the war of to-day with the tools of yesterday, nor, unfortunately, the war of to-morrow with the tools of to-day. The fundamental principles of warfare and combat remain ever the same; but the methods and means of attaining the ends desired are in a state of constant change and flux. It behooves us, therefore, to keep in touch with modern developments, so that, when a crisis comes, we may know definitely what is required and also what is not essential. Had this been done during past years this country would have saved vast sums of money, and much waste

effort would have been avoided. Production under emergency conditions is always expensive.

The lessons to be learned from our recent experiences along these lines are so obvious that comment is unnecessary. Such lessons are soon forgotten by the country at large. It is, however, essential that a written record be made of the war-time development of certain of the manufacturing problems as they confronted us and were solved. The record may serve a useful purpose and be of value in case of a future emergency.

The present report seeks to outline, in a general way, some of the factors which we encountered in the manufacture of optical glass and of lenses and prisms for fire-control and observational instruments for the Army and Navy. The presentation is necessarily general in character, emphasis being placed on underlying principles rather than on details. The report presents in substance the experience of the writer, who, with fellow scientists, entered as strangers into a new branch of endeavor to solve certain problems of a technical nature. Between the lines of the written record may be read many interesting experiences for the scientist in technical work and the gradual change in the attitude of practical factory men toward him. In all problems of high precision, whether technical or laboratory, the scientifically trained observer, who has learned to appreciate the factors essential to the attainment of high precision and is competent to control these factors, is able to undertake the job with better chance of success than the rule-of-thumb man of the shop who has the factory experience, but lacks the necessary training with which to meet new and radically different problems precipitated by war. In war-time organizations as in peace-time organizations the question of competent personnel is always the fundamental factor and the most difficult to meet satisfactorily. The experience of the recent war proved this statement time and again, and demonstrated the need for a closer and more effective touch between the Army and Navy and the scientific as well as the manufacturing forces of the country.

THE MANUFACTURING PROBLEM.

At the time of the entrance of the United States into the war, the methods and instruments of indirect artillery fire were already universally employed on the battle fronts and our troops had to be supplied with these instruments if they were to combat the enemy successfully. We were brought, in short, face to face with many technical manufacturing problems which had to be solved and placed on a production basis quickly if our Army and Navy were to get what they wanted when they needed it. Many of these problems arose because manufacturers before the war had been accustomed

to import supplies of this nature from Europe, especially Germany, and had never felt the need for developing the manufacturing processes in their own plants. Such development meant large expense and it was easier and cheaper to place an order for the commodity in Germany. This applied especially to highly technical products, such as dyes and optical glass.

Military fire-control apparatus includes instruments of high precision, and, as one of the integral parts of such instruments, optical glass must measure up to the same standards of high precision. Upon it the quality of the image formed and the precision of each setting of the sighting instrument is dependent. The lens designer computes the shapes and positions of the several different lenses and prisms in an optical instrument and arranges them along the line of sight in such a way that the particular and inevitable defects, or aberrations, are reduced to a minimum. The degree to which these aberrations can be made negligible depends in large measure on the kinds and quality of glass available to the designer. It is important, therefore, that the quality of the glass be of the best and that a sufficient number of different glass types be at hand.

Before the war the optical industry in this country was in the hands of a few firms. Several of these were under German influence and one firm was directly affiliated with the largest manufacturer of optical instruments in Germany; the workmen were largely Germans or of German origin; the kinds and design of apparatus produced were for the most part essentially European in character; optical glass was procured entirely from abroad and chiefly from Germany. Educational and research institutions obtained a large part of their equipment from Germany and offered no special inducement for American manufacturers to provide such apparatus. Duty-free importation favored and encouraged this dependence on Germany for scientific apparatus.

With our declaration of war the European sources of supply for optical glass and for optical instruments were cut off abruptly. Even before our entry into the war and especially after hostilities began in 1914, manufacturers of optical instruments realized that the European supply of optical glass might be stopped and they began experiments on its manufacture. In 1912 the Bausch & Lomb Optical Co., of Rochester, N. Y; in 1914 the Bureau of Standards at Pittsburgh, Pa.; in 1915 the Keuffel & Esser Co., of Hoboken, N. J., and the Pittsburgh Plate Glass Co., of Pittsburgh, Pa.; in 1916 the Spencer Lens Co., of Buffalo, N. Y., started work and produced some optical glass of fair quality. The quality of glass obtained was not, however, entirely satisfactory and by the time we entered the war, the shortage of optical glass of high quality was so serious that unless something were done speedily to relieve the situation, the Army and Navy would not be equipped with the necessary optical instruments.

Such was the situation in April, 1917. The fundamental item for fire-control instruments, optical glass, had not been produced satisfactorily in quantity in this country. The methods for its manufacture on a large scale had still to be developed. After the supply of optical glass had been assured the manufacturing capacity for precision optics had to be increased to a scale commensurate with the needs, and finally the design of new instruments required proper supervision with reference both to ultimate field use and to speed of production.

In this emergency the Government through the Council of National Defense appealed to the Geophysical Laboratory of the Carnegie Institution of Washington for assistance in the manufacture of optical glass. This research laboratory had been engaged for many years in the study of silicate solutions, similar to optical glass, at high temperatures, and had a corps of scientists trained along the lines essential to the successful production of optical glass. It was the only organization in the country with a personnel adequate and competent to render aid in a manufacturing problem of this character and magnitude. Obviously the best plan was to cooperate with manufacturers who had had some experience along these lines.

In order to ascertain the attitude of one of the manufacturers the writer visited on April 4, 1917, the Bausch & Lomb Optical Co., and found them willing to cooperate. Accordingly, when the request from the Government for aid was made shortly after war was declared, a group of scientists, with the writer in charge, went from the Geophysical Laboratory on April 27 to the Rochester plant and began work. Its men were gradually assigned to the different factory operations and made responsible for them. At this plant much of the pioneer development work was accomplished. The methods of manufacture on a large scale were here developed and placed on a production basis. Drs. Day, Allen, Bowen, Fenner, Hostetter, Lombard, Ferguson, Washington, Hall, Merwin, Morey, and Andersen were with us for longer or shorter periods of time to May, 1918. At the Geophysical Laboratory special problems were attacked by Drs. Allen, Zies, Posnjak, Bichowsky, Merwin, White, Roberts, Andersen, Adams, and Williamson. To the director of the laboratory, Dr. A. L. Day, fell the general executive problems involving laboratory personnel and the several phases of their activity in connection especially with the sources and transportation of suitable raw materials and of fuel. He was also instrumental in securing the cooperation of outside firms to undertake special jobs essential to the successful manufacture of optical glass.[1]

[1] For a detailed account of this important part of the task see the paper by A. L. Day on "Optical glass and its future as an American industry," J. Franklin Institute **190**, 453–472, 1920. See also Chapter VII by Harrison E. Howe on "Optical glass for war needs" in the book The New World of Science, edited by R. M. Yerkes and published by the Century Co. New York, 1920.

As a matter of record, establishing the connection of Ordnance Department with this task, it may be noted that in April, 1917, the writer received his captain's commission in the Engineer Reserve Corps; but, at the request of officers in the Ordnance Department, was transferred to the Ordnance Department. This direct connection with the Army aided the solution of the problem of glass manufacture in many ways. War-time experience has proved that direct Army and Navy connection with technical problems of this nature is invaluable. Under war conditions the court of last appeal is the Army and the Navy; in situations which arise requiring prompt and effective action it is useful to have this lever available, even though it may not be necessary to employ it.

Military optical instruments are for the most part telescopes; for their satisfactory design experience has shown that from three to five different types of optical glass suffice. The problem before us was essentially one of high-speed, quantity production of a relatively small number of glass types. We were not concerned with the development of new types of optical glass, but rather with the manufacture of only a few kinds, such as ordinary crown, borosilicate crown, light and dense barium crown, light and dense flint. Our task was to reproduce in this country glasses of standard type which had long been produced in Europe. The European methods of manufacture of these glasses, however, were not adequately known, and a large part of our time was devoted to the study and development of manufacturing processes which eventually enabled us to produce sufficient quantities of optical glass of high quality. The problem before us, although essentially a research problem, differed materially from ordinary research problems in that the properties of the final product were known in detail. After the manufacturing difficulties in connection with this problem had been overcome attention might well have been devoted to the development and manufacture of new types of optical glasses; but at that time the need for greater manufacturing capacity for optical instruments was so great that this phase of the situation demanded immediate attention.

Our first efforts at the Bausch & Lomb plant in April and May, 1917, were devoted to a study of the glass-making process and of the several factors involved. At the factory we had the hearty cooperation of Mr. William Bausch, to whom credit is due for having started the glass plant in 1912, and of Mr. Victor Martin, a practical Belgian glassmaker, who had placed the plant on a running basis and had produced, even in 1912, some optical glass of fair quality. Our task was to build up on Mr. Martin's experience and to introduce into the manufacturing process the element of high precision and control which were not sufficiently recognized, but which were essential to the manufacture of optical glass of uniformly high quality. Our task

was not strictly a development of new processes or of a new product, but rather the modification of existing processes as practiced at the plant so as to obtain satisfactory optical glass in large quantities.

The search for raw materials of adequate chemical purity in ton lots, the preparation and mixing of the batches, the control of the melting furnaces, of the pot arches, and of the annealing ovens; the stirring of the molten glass; the inspection of the product at the several stages; these and other problems had to be studied in detail and in each case exact information gained regarding the best practice to be followed. Soon after our arrival at the plant it was the writer's good fortune to deduce, as a result of a statistical study of the existing chemical analysis of optical glasses, certain relations which enabled us to write down at once the batch-composition for glasses of desired optical constants, especially in the flint series. This deduction freed our minds of the uncertainty regarding our ability to reproduce optical glasses of standard types, the batches of which were held secret by glass makers. Indirectly it had a much more important effect because it changed the attitude of the factory men toward us; they realized at once that the cut-and-try method, by which their few batch formulas had been obtained, was superseded by a more direct method of attack which gave us control over whole series of glasses rather than over a few isolated members of a series. Additional studies and analyses made at the Geophysical Laboratory have borne out the conclusions deduced from these preliminary studies.

The literature on the details of optical glass making is scant, and the processes have heretofore been considered secret and have been closely guarded. The problem before us was one of intense interest and great importance and we soon realized that what was most needed was precision control over all the steps in the manufacturing process. This was emphasized by the writer in Report No. 1, for the week ending May 5, 1917, and in many of the succeeding reports. Reports were prepared weekly on the progress made at the plant, and will be referred to hereafter simply by date and number.

By November, 1917, the manufacturing processes at the Bausch & Lomb plant had been developed, mastered, and placed on a production basis. Large quantities of optical glass of good quality were being produced. In December, 1917, the work was extended and men from the Geophysical Laboratory, who had been connected with the pioneer work at Rochester, took practical charge of the plants of the Spencer Lens Co. and of the Pittsburgh Plate Glass Co. At the Spencer lens plant Dr. C. N. Fenner produced excellent optical glass from the start and was very successful in placing the plant on a production basis and in extending its capacity manyfold. He was assisted at different times by Drs. Allen, Andersen, Bowen, Morey, and Zies, of the Geophysical Laboratory. In July, 1918, Dr. Morey relieved Dr. Fenner. At the Pittsburgh works Dr.

Hostetter was put in charge and was confronted with a most difficult problem in organization to convert and build up an old plate-glass plant into an effective system for the manufacture of optical glass. In this task he was assisted by Drs. Andersen, Adams, Bowen, Lombard, Morey, Roberts, Ferguson, Williamson, and Wright, of the Geophysical Laboratory; by Messrs. Taylor, Bleininger, and Kiess, of the Bureau of Standards; and by the staff of the Pittsburgh Plate Glass Co. In the course of some months the organization was accomplished. Much credit is due to these men for the success attained.

These details are given because they show how a highly technical problem of this kind was attacked under war-time conditions and solved successfully. The records show that at these three plants approximately 95 per cent of all the optical glass manufactured in this country during the war was produced.

In addition to the foregoing plants, optical glass was made by the Keuffel & Esser Co. in quantities sufficient to supply their own needs. Much credit is due Mr. Carl Keuffel, who, on his own initiative and before we entered the war, erected a glass-melting furnace, made suitable pots, and produced some glass of good quality without outside help.

Small quantities of optical glass were also made in furnaces at the Bureau of Standards at Pittsburgh. Dr. Bleininger developed at this plant a poured, porcelainlike crucible which proved to be satisfactory for use with the dense barium crown melts that attack ordinary clay pots vigorously.

Three other firms, the Hazel-Atlas Glass Co., at Washington, Pa.; the Carr-Lowrey Glass Co., of Baltimore; and the H. C. Fry Co., of Pittsburgh, Pa., experimented on the manufacture of optical glass, but did not reach the stage of quantity production.

In the solution of the optical glass problem, the expense incurred by the Geophysical Laboratory as a voluntary contribution to the Government amounted to about $200,000; at no time during the war or after, did the Geophysical Laboratory request or receive any money from the Government for these or other expenditures; but the results attained justified the expenditures. This could not have been done, however, without the hearty cooperation of the manufacturers, of the Army, especially of the Army Ordnance Department, and of the War Industries Board. The Bureau of Standards aided in the development of a chemically and thoroughly resistant crucible in which to melt optical glass; also in the testing of optical glass and especially in the testing of optical instruments. The United States Geological Survey aided in locating sources of raw materials, such as sand, of adequate purity.

The general situation may be summarized by stating that when we entered the war we not only lacked a supply of optical glass, but

we lacked information regarding the processes of its manufacture. We had little knowledge of the quality and sources of supply of the raw materials required. We lacked manufacturing capacity and a trained personnel to handle the problems. The problems to be solved required the cooperation and working together of many diverse elements; it was a constant source of inspiration for us to witness the whole-hearted spirit of cooperation of the manufacturers in this connection and especially of those manufacturers who were not directly concerned with the final product. The quantity production of a few standard types of optical glass of usable quality was our goal rather than the development of new and highly perfect types of optical glass. There is still room for improvement in many details; but the manufacturing processes are known; there are no secrets and the manufacture of optical glass has become one of factory routine. It is with satisfaction that all those who have contributed to this result may look and realize that one more commodity has been added to the list of commodities made in this country. This was accomplished, however, under high pressure and at large expense, part of which might have been saved had the problem been attacked under peace-time conditions.

The records show that there were produced in this country between April, 1917, and November, 1918, over 600,000 pounds of usable optical glass. Not all of this glass was of the best quality, but it was satisfactory for low-power optical instruments, and some of the product was of the highest quality, equal to the best European glass. On an average its quality was fair and satisfactory for war-time purposes. Six different types of glass were manufactured: Ordinary crown, borosilicate crown, barium crown, dense barium crown, light flint, and dense flint. The total monthly production statistics are listed in Table 1, and presented graphically in figure 1.

TABLE I.—*Estimated total production, in pounds, of usable optical glass (A and B quality) in the United States from April, 1917, to November, 1918.*

1917:	Pounds.	1918:	Pounds.
April	2,850	January	35,955
May	4,600	February	41,138
June	6,500	March	41,842
July	4,800	April	24,363
August	4,800	May	43,397
September	10,775	June	69,328
October	15,645	July	55,355
November	30,499	August	71,459
December	42,451	September	67,741
		October	79,275
Total for year	122,920	Total for year	529,853
		Total	655,773

Of these quantities the Bausch & Lomb Optical Co. produced over 65 per cent, the Pittsburgh Plate Glass Co. nearly 20 per cent; the Spencer Lens Co. nearly 10 per cent; the remaining 5 per cent was produced by the other firms, including the Bureau of Standards. The figures, especially those for 1917, are less accurate than those for 1918, but they are of the correct order of magnitude. The figures

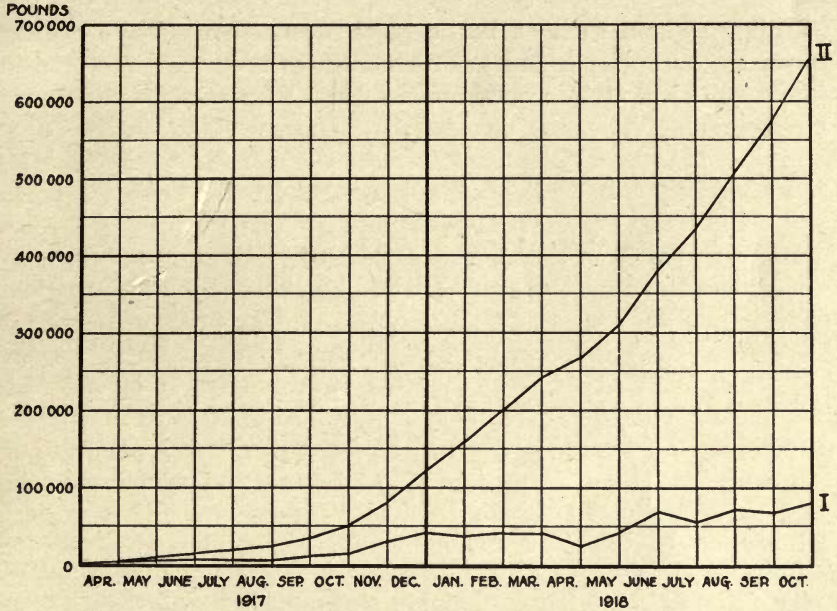

FIG. 1.—Curve I indicates the total monthly production of optical glass in the United States from April, 1917, to November, 1918; Curve II shows the cumulative total production of optical glass for the same period.

show that starting with the total monthly production of 1½ tons of usable glass in April, 1917, the monthly production mounted to about 40 tons in October, 1918; the organizations at that time were, moreover, so well coordinated that an increase of 50 per cent in the total monthly production could have been attained had the need arisen.

Chapter II.

THE CHARACTERISTICS OF OPTICAL GLASS.

Ordinary glass, such as bottle glass, decorative glass, etc., was known to the ancients and has for centuries been manufactured in large quantities; certain communities have been engaged in the art of glassmaking for many generations. Optical glass, on the other hand, is a modern development to meet the demand for better telescopes, microscopes, photographic lenses, and other optical apparatus. At first sight optical glass may appear to be simply glass, not greatly different from ordinary glass, but the differences between the two are fundamental and can best be apppreciated by an examination into the functions of optical glass as an integral part of an optical instrument; from these in turn the characteristics required of the glass which shall satisfy these conditions adequately can be deduced. It is not obvious at first thought why optical glass is so difficult to manufacture satisfactorily and why so much emphasis is placed upon its quality. A brief discussion of the factors, on which the performance of an optical system depends, will serve to render this clear and prepare the way for further comments on details of similar nature.

Most optical instruments employed in military operations are of the telescope type and serve not only to aid the observer in detecting details of distant objects, but also to fix with high precision reference lines of sight and thus enable the gunner to direct and to control the fire of his fieldpieces.

THE FUNCTIONS OF THE EYE.

The function of a telescopic lens system is similar to that of the eye. We see a distant point because light waves emerge from it or are reflected by it; each point of the object is seen as a point because the eye unites to a point on the retina the waves of light from the object point which impinge on the eyelens. What we actually see is the image formed on the retina of the eye as focused there by its converging lens system. (Fig. 2*a*.) In case the eye is defective such points are not imaged as points on the retina; thus in the eye in repose (adjusted to see distant objects) the retina may be too near the eyelens (farsighted eye) (fig. 2*b*), or it may be too far from the eyelens (nearsighted eye) (fig. 2*c*), or the surfaces of the eyelens may not be spherical but warped so that the converging effect in one meridian is

different from that in another (astigmatic eye). The farsighted eye is "corrected" by means of a collective or positive spectacle lens (indicated by dotted lines in fig. 2*b*); the nearsighted eye by a dispersive or negative lens (fig. 2*c*), and the astigmatic eye by a cylindrical lens. The eye resembles a photographic camera in certain respects. The lens system of the normal eye converges rays from a distant point to a point on the retina which in turn responds to the light-wave impulses and functions as a receiving transformer converting the light-wave impulses into nerve impulses which travel to the brain and are

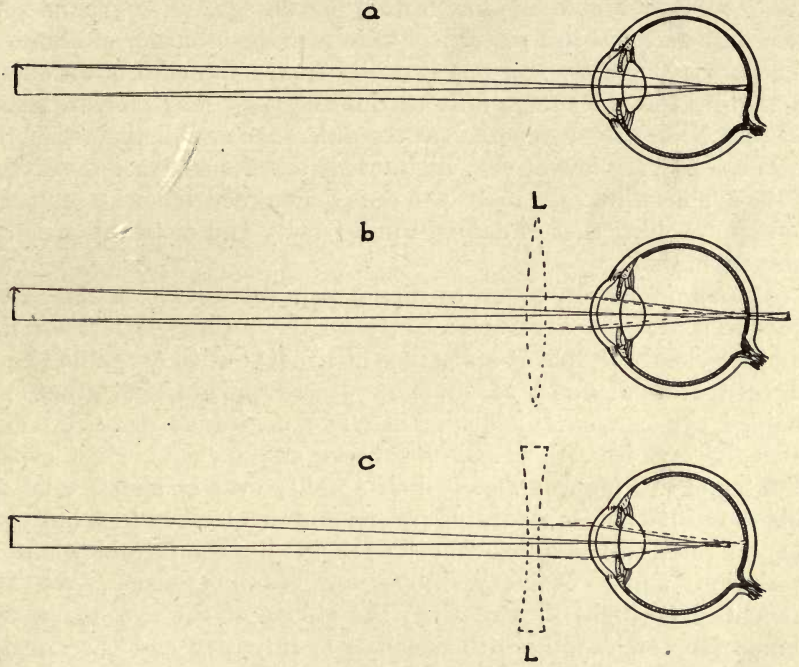

FIG. 2.—Diagrams illustrating action of eyelens in forming image of distant object on the retina. Fig. 2*a* shows action of a normal eye in which the image is focused on the retina itself. In fig. 2*b* the image plane is located back of the retina (far-sighted eye), while in fig. 2*c* the image plane is in front of the retina. The dotted lines in fig. 2*b* and 2*c* illustrate the action of spectacle lenses in increasing (fig. 2*b*) or decreasing (fig. 2*c*) the convergence of the incident rays.

there interpreted. The retina is to the eye what the photographic plate is to the camera.

The eye is an integral part of all optical observing instruments; and these in turn should present to the eye images for observation which approach in characteristics the conditions under which the eye has been accustomed from childhood to function. These fundamental conditions may be considered under three heads:

1. Intensity of illumination or brightness.
2. Resolving power or definition.
3. Field of view.

(1) *Intensity of illumination.*—For good seeing the intensity of the light emerging from each object point (brightness of object) should not be too weak (twilight illumination) nor too strong. The adaptability of the eye to differences in intensity is most remarkable; it operates satisfactorily over a range of intensities from 1 to 10,000,000. We see the details of an object because of differences in brightness (contrast in light and shade) and in color. Under ordinary conditions of illumination the eye is sensitive to a difference of about 2 per cent in brightness between two adjacent points; under very favorable conditions this percentage difference in contrast may decrease to 1 per cent, but in case the intensity of illumination passes gradually and not abruptly from one detail of an object to another the percentage difference in intensity may increase many per cent before the eye perceives the difference and distinguishes the details. At very low or very high intensities the contrast sensibility of the eye may increase to 10 per cent. For good vision an illumination approaching that of daylight in intensity and distribution is the most favorable.

(2) *Definition.*—In order to distinguish the details of an object these must exceed a certain size; thus the printed letters on this page are clearly legible at a distance of 1 foot; but they can no longer be read at a distance of 10 feet. Measurements show that the unaided eye can readily distinguish two points as distinct points when the rays from these points subtend at the eye an angle of two minutes of arc (approximately half a mil); eyes of high acuity are able to resolve points separated by one minute of arc or less; but, as a general rule, two minutes may be taken as a comfortable limit of resolution under ordinary intensities of illumination. At low intensities (twilight illumination) the ability of the eye to resolve details falls off rapidly with decrease in intensity and the angular separation of points just discernible as distinct points may rise to several degrees. This is readily tested by noting that the headlines of a newspaper can still be read in twilight after the fine print has become completely illegible. It is for this reason especially that in faint illumination a telescope or field glass enables the eye to distinguish details which it can not see otherwise; and this in spite of the fact that a considerable amount of the incident light is lost by reflection and absorption in the elements of the telescope system itself. In the section on the telescope lens system the explanation of this apparent anomaly is given in some detail.

It is shown in textbooks on physics that each image point formed by a lens such as the eye, the photographic lens, the telescope, or the microscope objective is in reality a diffraction pattern to which the rays from each object point contribute; thus the image of a luminous point, such as a star, is actually a central disk of light

surrounded by a set of concentric dark and light rings. Experience shows that the images from two such points, such as a double star, can be distinguished or resolved when the central disk of the one image touches the first dark ring in the image of the second. This theoretical limit of resolution depends directly on the wave length of light used and inversely on the aperture of the lens. In the eye the lens aperture is varied by means of the iris which serves also to shield the eye from too intense illumination; the diameter of the iris (pupillary aperture) ranges from 2 to 8 millimeters.

Any defect in a lens which tends to decrease the theoretical limit of resolution is serious; but such defects are inherent in all lenses and the lens designer aims to reduce these defects or aberrations to a limit at least equal to that of the eye itself. The importance of the eye as an essential part of an observing instrument is obvious; but the need for training the eye to do its part and the desirability of fulfilling certain conditions requisite for the attainment of the best definition are not always realized, especially by observers in the field.

3. *Field of view.*—The eyes grasp at a glance a certain area or field of view, and thus enable the observer to perceive the relative positions of points and objects in space. The normal eye at rest is focused for parallel rays, i. e., rays from distant points; it accommodates, however, with extreme rapidity for points distant only 10 inches, the distance of near vision. Experiments show that the field of sharpest vision is only $\frac{1}{2}°$, corresponding to the area of the yellow spot on the retina; but, as a result of persistence of vision and mobility of the eye in its socket, the field covered satisfactorily is nearly 30° horizontal and 20° vertical; this is surrounded by a field of visual perception but indistinct vision which extends to 150° horizontal and 120° vertical in the single eye. In observing instruments the apparent field of view should approximate at least the angular area of satisfactory vision and preferably a larger area because the eye by reason of its mobility in changing its line of sight easily covers larger angular fields of view.

To recapitulate: Three factors, *intensity of illumination, definition,* and *field of view,* are fundamental to satisfactory vision.

THE LENS SYSTEM OF A TELESCOPE.

In the design of an optical observing instrument these factors are likewise fundamental; in addition, a fourth factor, namely, *magnification* is equally fundamental. The objective of the telescope functions as the eye of the instrument. Its area is much larger than that of the pupil of the eye; hence a correspondingly larger number of light waves from each distant object point impinge on it. The objective should be so designed that it converges the rays which it receives from each distant point to a corresponding point in the

image plane. (Fig. 3.) The image thus formed is the aggregate of the points of convergence of pencils of rays received by the objective from distant object points. By thus imaging the object points, they are, as it were, brought to a position much nearer the observer, and can there be examined by him with the aid of a magnifying lens. (Eyepiece, fig. 3.) By this means the eye approaches in effect close to the image and the angle subtended at the eye by any two points in the image is correspondingly increased. The ratio of the angle subtended at the eye between two points in the image to the angle at the eye between the corresponding points of the distant object is a measure of the angular magnifying power of the telescope. Thus, if the angle of separation between two distant points, as viewed by the unaided eye, is 2 minutes of arc, this apparent angle of separation when viewed through a telescope may be 20 minutes of arc; in this case the magnifying power of the telescope is 10. The angle between two object points actually separated by only 12 seconds of arc (0.2 of a minute) at the observer's eye appears through this telescope (10 power) to be separated by 2 minutes of arc; these points

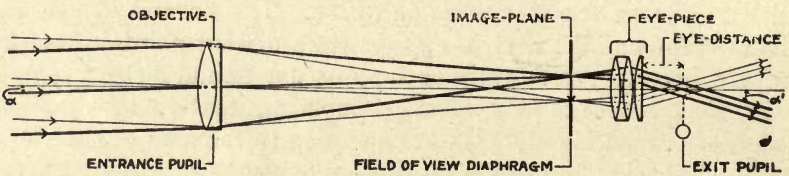

FIG. 3.—Sectional view of the optical elements of a telescope lens system, showing paths of rays through the system.

are therefore readily distinguished as separate points with the aid of the telescope. The apparent field of a 6-power binocular is 48°; the actual field is 8°, only one-sixth as large.

In a telescope the area of the image is limited by a circular stop or diaphragm located in the image plane; this is called the *field of view diaphragm;* it is imaged on the retina and effectively excludes the rays from object points outside of the area imaged. This diaphragm functions similarly to the porthole in a ship's cabin in limiting the field of view, and has been called the *entrance port* or *window* of the instrument; it is evident that the farther away the eye is from the porthole or window the smaller is the angular field of view.

The pencils of rays from distant object points enter the telescope through the objective and are limited in width either by the rim of the objective or by some smaller stop which is called the *entrance pupil* of the instrument; this, like the iris of the eye, limits the cone of light which a given object point sends through the instrument; the image of this stop (entrance pupil), as seen through the eyepiece end of the telescope, is called the *exit pupil.* The rays from all points in the image cross at the exit pupil; if the observer's eye is placed

there, the entire image can be seen without lateral shift of the eye; if the eye is placed elsewhere it must be shifted from side to side in order to see the entire field. It is important, therefore, for ease of observation that the iris of the eye coincide in position with the exit pupil of the instrument. If a telescope of the ordinary type is pointed at the sky, the exit pupil can be seen as a disk of light suspended in air a short distance back of the eyepiece.

The telescope is primarily a light-collecting device to concentrate on the pupil of the eye a greater quantity of light from an object point than the eye would otherwise receive. At the same time the angular separation of the object points, as seen in the image, is increased. Mere magnification of the size of the image, however, without corresponding increase in illumination serves little purpose. Hence the general rule that the best power to use is the lowest power which enables the eye to see the details of the object. With this power the size of the exit pupil is larger than with higher powers and the image appears to the eye brighter and more readily seen.

The quantity of light entering a telescope depends in general directly on the area of its entrance pupil, and this is commonly the objective itself. The relative light-gathering power of two telescope objectives varies accordingly as their areas or as the squares of their diameters. The relative quantities of light from a distant object point, such as a star, flowing into a telescope objective of 1-inch (25.4 mm.) aperture and the pupil of the eye of $\frac{1}{5}$ inch (5 mm.) aperture are accordingly as 25 to 1. Similarly a 2-inch objective collects 4 times as much light as a 1-inch objective and 100 times as much as the eye; a 3-inch objective, 9 times as much as the 1-inch and 225 times as much as the eye. From this it may be concluded that, since in a telescope the ratio of the diameter of its entrance pupil (ordinarily diameter of objective) to that of its exit pupil (eye circle) is a measure of its magnifying power, a linear magnification of 10 diameters (one hundredfold magnification of corresponding image areas) is the most favorable in a 2-inch objective. In this case the full resolving power of the eye is utilized. Although an appreciable amount of light is lost on its passage through the telescope lens system, experience has proved that for field purposes this degree of magnification is satisfactory. On the other hand, the magnification should not be so low that the size of the exit pupil exceeds appreciably that of the eye pupil, which at a maximum is 8 millimeters in diameter. In the Army type 6 by 30 binocular field-glass the magnification is 6 diameters; the diameter of its objective is 30 millimeters; the diameter of its exit pupil is accordingly 5 millimeters.

To recapitulate: The size of the objective in a telescope determines in general the quantity of light which enters the eye through the

exit pupil. This, in turn, should be approximately equal in area to that of the pupillary aperture of the eye. If it is much larger, some of the light is lost; if much smaller, the subjective brightness of the image is decreased and the resolving power of the eye is not fully utilized. The magnifying power of the telescope should be so chosen that its exit pupil is approximately equal to the pupillary aperture of the eye. The visual brightness of an image can never be greater than that produced by the object itself on the retina; but the fact that the telescope objective concentrates a much larger cone of rays from each object point than does the eye, and at the same time increases the angular separation of these points in the ratio of the magnifying power, accounts for the lack of decrease in apparent brightness which one might expect with increase in magnification. It also explains the fact that many stars invisible to the unaided eye are readily seen through a telescope, and this in spite of the loss of an appreciable quantity of light by absorption and reflection in the telescope itself. In the case of a fixed star, the star remains a point or diffraction disk even under the highest powers; but, because the telescope gathers a large amount of light, its effect is to produce a correspondingly increased sensation of light on the retina. The luminous stimulus must exceed a certain limit of light energy flux (about 0.001 meter-candle) in order to produce the sensation of light in the eye. For energy fluxes below this limit the eye fails to respond and the luminous point is not visible. The larger the diameter of the telescope lens the greater is its resolving power, and the fainter are the stars which are visible. In twilight illumination details of objects are more readily discerned through a binocular than with the unaided eye, chiefly because of increased angular separation of the details accompanied by an increase in brightness to offset the increase in size of the retinal image.

In the design of a telescope lens system the effort is made to obtain an apparent field of view which is comparable to that of the unaided eye. The apparent angular field of view (actual field of view times the magnification) ranges in telescopes from 15° to 50°. The higher the magnification the smaller the actual angle subtended at the telescope between points at opposite margins of the field.

THE QUALITY OF THE IMAGE.

The ideal image, as formed by the objective of a telescope, is one similar in every respect to the distant object, so that, when viewed through the eyepiece, the image produced on the retina of the eye is a correct and enlarged picture of that received on the retina when viewed by the unaided eye. There are, however, a number of factors which render it impossible actually to attain this ideal; but in modern lens systems it is possible to approach so closely to it that

the definition attained is as good as the eye is capable of perceiving, and for practical purposes this suffices. A brief summary of the several defects of the image will indicate some of the factors with which the lens designer and lens constructor have to contend. It is customary to consider, under separate headings, the defects or aberrations affecting image points situated along the axis (line of sight) of the instrument and the defects for points removed from the axis. These aberrations occur for each color of light employed. The defects arising from the use of white light are designated chromatic aberrations in contrast to the aberrations which are present when light of only one color (monochromatic light) is employed.

The significance of the several aberrations of a lens is most readily presented by considering first its action on extremely narrow pencils of light rays entering indefinitely near the axis (first order theory) and then deducing the effects produced on wider pencils and larger apertures (third order theory). Gauss showed that for the first

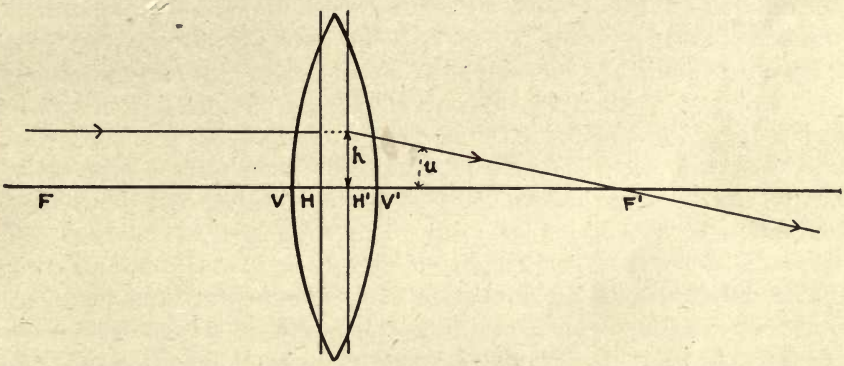

FIG. 4.—Diagram illustrating the principal Gauss points H and H' (planes), and the principal foci, F and F', of a lens for paraxial rays.

case the effect of the lens may be completely defined by reference to six points on the axis, namely, two focal points, two principal points, and two nodal points. If the lens is surrounded by air and the refringence of the medium for the entering rays is the same as that for the emergent rays, the nodal points coincide in position with the principal points, and the lens or lens system may be replaced for purposes of computation by its two foci, F, F', and its two principal points H, H'; thus in figure 4, F and F' are the two foci and H and H', the principal points (also nodal points). The equivalent focal length of the lens is $F\,H = F'\,H'$; its external focal lengths are FV and $F'V'$. If light of different colors be used it is found that rays of different color intersect the axis at points near F', but not exactly coinciding with it. This variation in the position of the focus or distance of the focus from the rear surface of the lens (external focal length) with change in wave length is called *chromatic aberration*. It is also found that the position of H' changes slightly

with the color of the light, so that even if the lens were corrected for chromatic aberration the focal distance H' F' varies with the color; this is called chromatic difference of focal length or *chromatic differences of magnification.*

If the pencil of light from a distant object point on the axis is not indefinitely narrow but is sufficiently wide to transmit an appreciable amount of light, so that at F' there is formed an image point which can be seen, it is found that the marginal rays intersect the axis near F' but not exactly at F'; this change in the position of the focus for rays of different aperture is called *spherical aberration,* and like chromatic aberration means a variation in external focal lengths. In a lens corrected for spherical aberration a distant object point on the axis is imaged as a single point on the axis. If it is desired to produce a single image point of a distant object point situated slightly off the axis, it is essential that the lengths of the optical paths of all rays from the object point to the image point be equal; this will be the case, as Abbe was the first to show, when, for each ray, the ratio of the sine of its opening angle (i. e. angle between axis and ray diverging from object point) to the sine of its closing angle (i. e. angle between axis and ray converging to conjugate image point) is a constant. For a distant object point the entering rays are practically parallel, and the Abbe sine condition is equivalent practically to the statement that the focal length, and hence the imagination of the lens for different zones, is constant. The four aberrations, namely, spherical aberration, sine condition, chromatic aberration, and chromatic differences of magnification are fundamental; but there are other aberrations which are important and merit consideration. In the following paragraphs a description of these aberrations is given, together with a somewhat different treatment of the four aberrations noted above.

MONOCHROMATIC ABERRATIONS.

The important monochromatic aberrations are five in number. It is not possible to eliminate them all in any one system and they are not all equally important in any given instrument; the lens designer endeavors, therefore, to reduce to a minimum those aberrations that are serious for the special type of lens system he desires. The five monochromatic aberrations are: (1) Aberration of a point on the axis (spherical aberration), (2) aberration of points removed from the axis (coma, sine condition), (3) astigmatism, (4) curvature of field, (5) distortion. The effects of these aberrations are illustrated in figure 5, *a* to *h*.

1. *Axial spherical aberration.*—In a simple collective lens (fig. 5*a*) refraction at the periphery causes rays near the margin to converge toward an axial point nearer the lens than the point for central axial

rays. The lens exhibits an excess of convergence for peripheral rays. A simple dispersive lens, on the other hand, exhibits an excess diverging effect for the peripheral rays. (Fig. 5*b*.) The result in both cases is to produce a general lack of sharpness in the image. This is called *spherical aberration*, longitudinal or axial. It is overcome in an objective by combining a collective lens with a dispersive lens as indicated by figure 5*c* so that the excess converging effect of the collective lens is neutralized by that of opposite character in the dispersive lens. The axial point of convergence for a beam of parallel incident rays is called the focal point or the focus of the lens. In correcting for spherical aberration the designer may cause the marginal rays to focus at a point beyond the point of convergence of the central rays (fig. 5*d*); the combination is said then to be spherically *overcorrected*. Figure 5*a* illustrates a spherically *undercorrected* lens. An objective may focus both central and marginal rays at one point and fail to do so for intermediate rays (fig. 5*e*); the lens is then said to show *spherical zones*. Correction of spherical aberration can be effected for only one pair of conjugate planes.

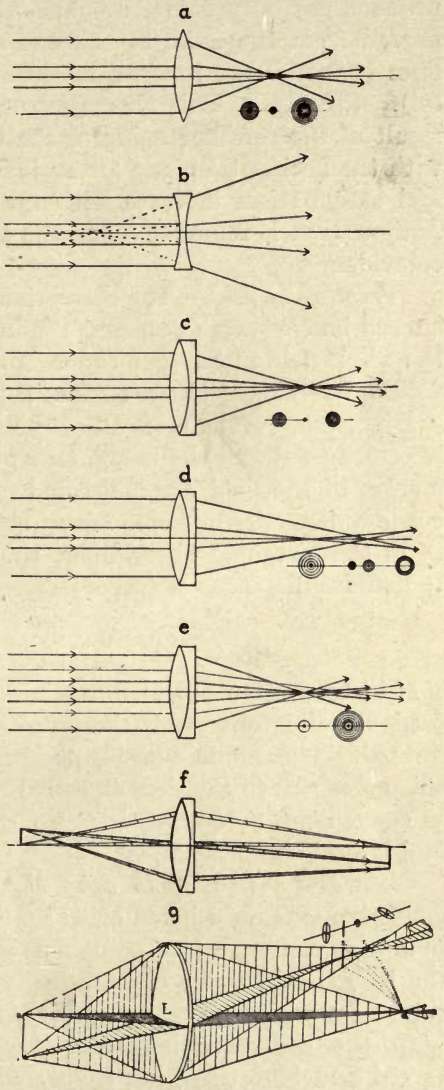

FIG. 5.—(*a*) Spherical aberration in a single collective (positive) lens. (*b*) Spherical aberration in a single dispersive (negative) lens. (*c*) Doublet corrected for spherical aberration. (*d*) Spherical overcorrection in a doublet. (*e*) Spherical zones in a doublet corrected for spherical aberration. (*f*) Coma in a lens. Lack of fulfillment of sine condition. (*g*) Astigmatism in a lens.

2. *Coma, sine condition.*—The effect of an uncorrected lens on oblique rays from a point removed from the axis is to image the central rays at one point, and the marginal rays nearer or farther away from the axis. (Fig. 5*f*.) Even though the lens is corrected for axial spherical aberration, it may show lateral spherical aberration for extra-axial points, and the effect is then to draw out the image of the point

so that it resembles a comet with its tail directed toward, or away from, the axis. This defect is known as *coma*.

Astigmatism.—The effect of a lens system on oblique rays is to produce not only coma, but also two sets of images for points removed from the axis; in the one set (inner image surface) radial lines (vertical) are imaged, in the second, tangential lines (horizontal). (Fig. 5*g*.) This aberration may be considered to follow as a result of the foreshortening of the lens in the vertical as compared with the horizontal plane for an inclined beam of light. Both coma and astigmatism increase with the obliquity of the incident rays. Astigmatism is removed when the two focal surfaces are brought to coincidence.

Curvature of field.—The correction for astigmatism may result in a curved image surface, so that the image is not entirely in focus over the whole field at any one time. In the lens corrected for flatness of field, however, the image surface is plane.

Distortion.—Even after all of the above aberrations have been satisfactorily reduced the image may be distorted so that points on the margin of the field are magnified more than the central area (pincushion distortion) or vice versa (barrel-shaped distortion). In this, as in the foregoing aberrations, the complete elimination is limited to definite distances of the object.

CHROMATIC ABERRATIONS.

If instead of an object illuminated by monochromatic light a colored object is observed, there is for each color of light an image formed. These images are superimposed and are in different planes; this gives rise to the defects called *chromatic aberrations*, of which it is convenient to distinguish two cases, namely, axial chromatism and lateral chromatism.

Chromatic aberration or axial chromatism.—The effect of a simple collective lens on a beam of white light is shown in figure 6*a*. The blue rays converge to a point nearer the lens than the red rays and the lens is said to be chromatically undercorrected. To neutralize this effect a dispersive lens of higher relative dispersion is combined with the collective lens (fig. 6*b*) and rays of two colors, such as red and blue emerging from a given axial object point, proceed to the same image point on the axis. A lens corrected for two colors is called achromatic; the departure from exact convergence, to an image point, of rays other than the two for which the lens is corrected gives rise to colored borders on the image; these residual color errors are called "secondary spectrum." By the use of optical glasses in which the partial dispersion ratios in the two glasses are nearly identical throughout the spectrum, rays of these colors can

be imaged at practically one image point, and only negligible colors of the tertiary spectrum remain.

Chromatic differences of magnification; lateral chromatism.—For points removed from the axis the corresponding image points may be displaced laterally by different amounts as a result of the differences in magnification with different colors so that the size of the image for blue light is different from that for red light; this gives rise to color fringes toward the margin of the field (fig. 6*c*). In the microscope this error, which is characteristic of apochromatic ob-

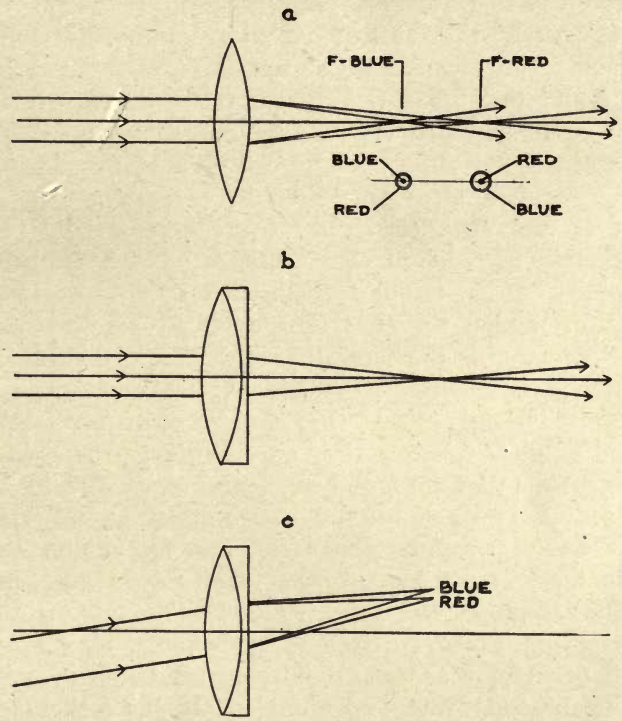

FIG. 6.—(*a*) Chromatic aberration in a single collective lens. (*b*) Doublet corrected for axial chromatism. (*c*) Chromatic differences of magnification or lateral chromatism in a doublet.

jectives, is neutralized by the use of compensating eyepieces in which the chromatic differences of magnification are of the same magnitude as those of the objective, but of opposite character.

The materials of which optical lens and prism systems are made must satisfy extremely rigid requirements of high precision; the character of workmanship in the grinding, polishing, and adjusting of the several elements of a lens system must also be good in order to conform to the specifications imposed by the lens designer. In common with other factory operations requiring a high degree of technical skill, a considerable amount of experience is required to ascertain and to maintain the best methods for accomplishing the

ends desired. Under war-time conditions this can be secured only by adequate realization of the principles involved and by a certain inventive adaptability on the part of the men concerned to make the best of the facilities at hand and to develop new facilities at the required speed.

THE CHARACTERISTICS OF OPTICAL GLASS.

Optical glass, as used in lenses and prisms, functions as a medium so to refract the rays of light from any distant object point that they will converge to a single corresponding point in the image. This condition is extremely difficult to meet and requires that the glass in each lens or prism element be of uniform quality and properties throughout and that its optical constants agree very closely with those of certain standard types of glass. To manufacture, on a large scale, a series of different types of glass of this degree of perfection requires close attention to details.

The art of making optical glass consists essentially in melting together certain ingredients at a sufficiently high temperature to insure liquidity so that bubbles which are formed rise to the surface and escape, of mixing the melt thoroughly by vigorous stirring so that its composition is the same throughout, and then allowing the pot of molten glass (600 to 3,500 pounds) to cool down slowly to room temperature. The ingredients that are put into the batch depend on the kind of glass desired; they are essentially the oxides or the salts of the metals that are found in natural rocks, and include silica (as sand), sodium and potassium oxides (as nitrates and carbonates), calcium oxide (as calcium carbonate), and aluminium oxide. In addition to these oxides certain other oxides are used to impart to the glass special properties; these include lead oxide (as red lead or litharge), barium oxide (as barium carbonate), zinc oxide, boric oxide (as hydroxide, or as borax), antimony and arsenic oxide, rarely a little manganese (as MnO_2), selenium, cobalt, and nickel (as oxides), and in some glasses fluorine (as a fluoride). A glass that contains an appreciable amount of lead is called *flint* glass, otherwise it is *crown* glass; thus we have series of ordinary flint glasses, of barium flints, of borosilicate flints; of ordinary crowns, of silicate crowns, of borosilicate crowns, of barium crowns, etc. These glasses have different refractive indices and different relative dispersions and are used in combination in lens and prism systems to reduce to a minimum the aberrations peculiar to the special optical system under design. The quality of performance of the lens system depends on the skill of the lens designer and the lens maker, and also on the quality and variety in types of glasses available.

The characteristics of good optical glass are:

Homogeneity:
- (*a*) Uniformity in chemical composition—
  1. Freedom from striæ.
  2. Freedom from bubbles.
  3. Freedom from inclusions, stones, and crystallites.
  4. Freedom from cloudiness.
- (*b*) Uniformity in physical state—
  1. Freedom from strains.

II. Definite refractive indices for different wave lengths:
- (*a*) Refractivity.
- (*b*) Dispersivity and dispersion ratios.

III. Freedom from color.

IV. High degree of transparency.

V. High degree of chemical and physical stability:
- (*a*) Resistance to action of weather and certain chemical agents.
- (*b*) Toughness and hardness.

I. HOMOGENEITY.

A fundamental requirement for optical glass is homogeneity; even a slight departure from a high degree of uniformity in composition is not tolerated because of the effect on the performance of the finished optical instrument. Compared with other kinds of glass, optical glass is a thing of extreme precision; the entire manufacturing process of optical glass has been developed with the object of attaining a highly homogeneous product. A number of factors enter into the problem; neglect of any one of these may render the glass unsuitable and useless for optical purposes. These factors will now be considered in some detail; appreciation of their significance is essential to a proper understanding of the several steps of the manufacturing process. Lack of chemical homogeneity finds expression in striæ, veins, cords, ream; in bubbles, seeds, air bells, boil; in stones and other inclusions, such as crystallites, and in strained glass.

(a) UNIFORMITY IN CHEMICAL COMPOSITION.

1. *Striæ (veins, cords, threads, ribbons, ream, etc.).*—Striæ are streaks of different composition within the glass mass; they represent either original differences in composition (resulting from insufficient mixing of the batch or from selective settling of batch elements during melting; these differences the stirring process failed to eradicate entirely) or differences arising either from materials introduced into the melt because of solution of the pot or from the volatilization of certain components of the melt whereby local differences in concentration are produced. Striæ are generally lower in refractive index than the inclosing glass; the differences in refractive index are commonly limited to the fourth decimal place; but in the case of heavy striæ they may increase to several units in

the third decimal place. (Fig. 7.) In one instance the refractive index of a very heavy cord was found to be 0.007 less than that of

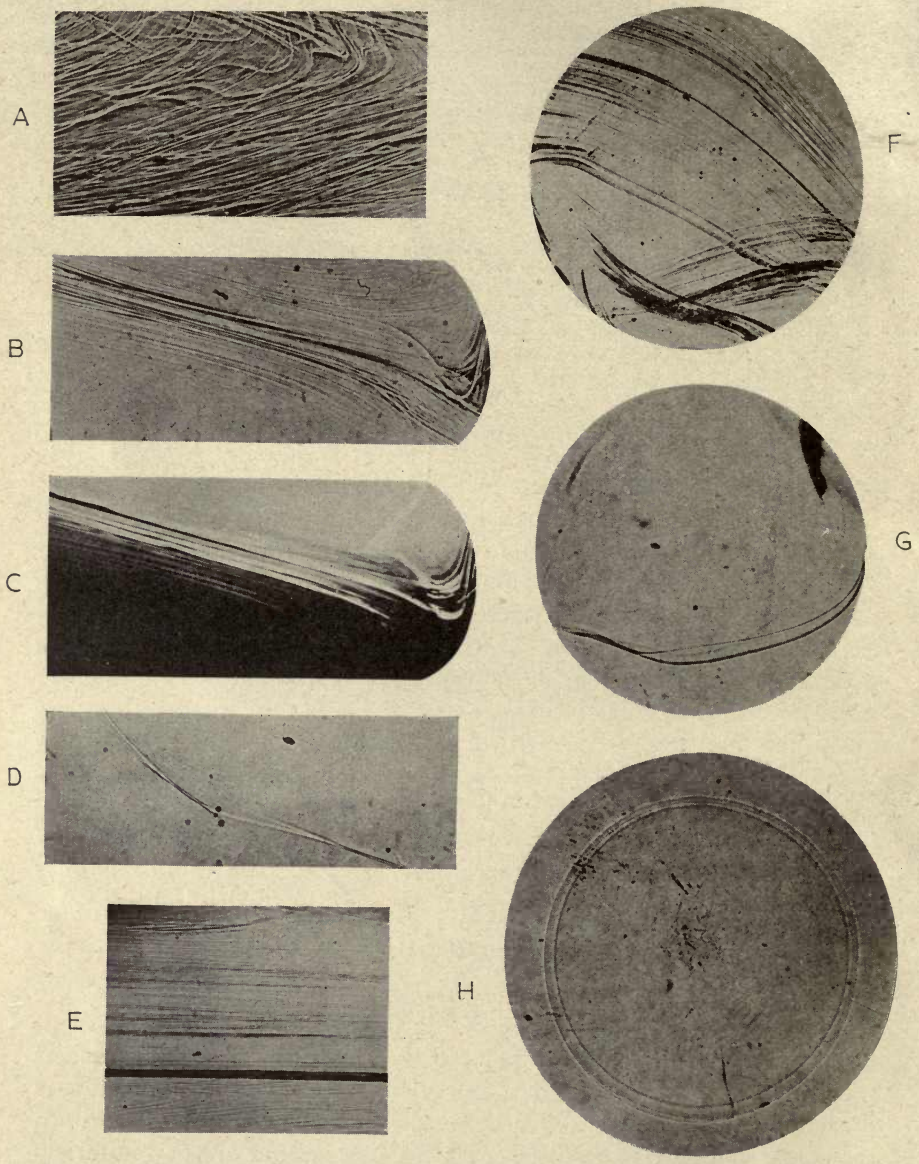

FIG. 7.—(*a*) Heavy striæ in a plate of glass. (*b*) Ribbon striæ (central illumination). (*c*) Ribbon striæ (oblique illumination). (*d*) Cord in a plate of glass; stone with striæ streamers near top of plate. (*e*) Ream in rolled optical glass. (*f*) Heavy striæ in a lens. (*g*) Cord and pressing defect in a lens. (*h*) Ream cut across by the steep curve of a negative lens.

the surrounding glass. As a result of these differences, the paths of the transmitted light rays are deflected slightly and to this extent the quality of the image is impaired. The effect of very slight

differences in refractive index, even in the fifth decimal place, is readily seen on a warm day, when hot ascending air currents render distant objects indistinct and destroy sharp definition.[2]

Because of their different refringences striæ disturb the paths of transmitted light rays slightly so that these rays no longer hit the exact point of the image they are supposed to hit; but they miss it by a very little; each point of the image may suffer similarly and the result is a decrease in sharpness over the entire field. In the case of high-power instruments the rays converge to an image point under a very small angle and a slight deviation in path seriously affects the quality of the image; in low-power instruments the rays converge to the image points under a larger angle and the same amount of angular deviation may be practically negligible. For this reason it is essential that for optical measuring instruments of precision, such as range finders, panoramic sights, etc., optical glass of the best quality only be used; for low-power visual instruments, such as trench telescopes, glass of second quality may not be objectionable for certain lens elements.

Experience has shown that the optical effect of fine striæ or even of heavy striæ in optical glass depends on their position and abundance in the particular optical element in which they appear. In the case of heavy cords or ribbons whose composition is noticeably different from that of the adjacent glass, their effect on transmitted light rays is so serious that the glass is worthless for optical purposes. A single heavy cord located near the margin or even at the center of a lens deflects and renders useless only a small fraction of the transmitted light and may have no perceptible effect on the definition; if the cord is in the objective lens, it is imaged near the exit pupil of the instrument and, although not visible, functions as would a piece of thread or wire placed directly in front of the eye. If the stria appears near the image plane, it is seen directly and destroys the definition along its path. In the case of fine striæ the effect depends largely on their character; it may be negligible for certain elements in low-power optical instruments. In photographic lenses of precision fine striæ in a lens element enlarge the circle of confusion for image points to such an extent that sharp definition is destroyed; a single heavy thread, on the other hand, simply deflects a small amount of light and does not cause appreciable deterioration of the image.

The effect of the presence of striæ in prisms depends on the type of striæ and on their position in the prisms, also on the type of the prism. In the case of individual threads which are sharply defined, the

[2] An interesting paper on the "Optical conditions accompanying the striæ which appear as imperfections in optical glass" has recently been published by A. A. Michelson in Scientific Paper No. 333, U. S. Bureau of Standards, 1919.

effect is simply to cut off a small amount of light and is not sufficient to cause perceptible decrease in illumination or definition. In the case of heavy striæ a large part of the light suffers deflection and the image of a distant object examined through the prism and an observing telescope may be doubled or appear to be badly astigmatic; fine-banded striæ may give rise also to a general flare, resembling that from coma, over the field. In the case of fine striæ the effect may be negligible or it may be so serious that the definition is spoiled; if the fine striæ are residual remnants of heavy cords which have not been completely dissolved, they may be surrounded by glass whose composition and refringence changes gradually in the vicinity of the striæ. A change of this kind in composition and refractivity is serious because it warps a transmitted light wave and renders sharp definition impossible. Under ordinary conditions of test such changes in composition are moreover not readily detected.

In the testing of prisms one is impressed with the variety and number of striæ which may be present and yet have no perceptible effect on definition in the image; whereas in other prisms even very faint striæ affect the quality of the image seriously. A heavy stria in an objective prism of a range finder may, if located near the margin, have no perceptible effect on the image; but the same stria situated at the center of the prism affects the definition so seriously that the prism is worthless. In the case of large objective prisms, the incident light rays are practically parallel and it is essential that the quality of the reflecting prism be of the best, otherwise astigmatism, double images, flare, and other defects are introduced into the image. The same holds true of roof-angle and other prisms in which each light ray traverses the prism in more than one plane. Glass for such prisms should be entirely free from striæ of any kind, otherwise the resolving power of the instrument containing such prisms may be seriously impaired.

In the case of fine-banded striæ, called "ream" by the plate-glass maker, experience has shown that if the planes of the ream are normal to the line of sight the quality of the image is not appreciably affected by the presence of ream. For example, the protecting windows or shields and the reticules of certain fire-control instruments are commonly made of selected plate glass, which is characterized by the presence of bands and ribbons of fine striæ approximately parallel with the polished surfaces. The crown lenses of many eyepieces are made of molded rolled glass. All spectacle lenses are made from molded rolled glass, not from stirred optical glass. Experience has shown that in many low-power optical instruments the use of rolled glass for relatively flat lenses of large curvature is permissible, especially if the lenses before grinding be molded to approximately the final shape. For lenses of deep curvature it is not good practice to use average quality rolled glass, because the heavy reams are cut

across and function there as ordinary striæ causing double images, etc. (Fig. 7*h*.)

The fact that a stria of a certain kind may destroy the usefulness of a prism or lens when located in one position is in general sufficient to bar it out entirely even though it would not be serious were it located in another part of the lens or prism. It is better policy in manufacture to eliminate raw, unworked material which is defective than to discard it later after much labor and expense have been put on it to produce finished optics. The probability that the striæ will be favorably located in the finished lens or prism is not sufficiently great to make the risk worth the while.

A less tangible but more serious defect in optical glass than striæ is the gradual change from point to point in its refringence. This may be present in optical glass in which no striæ are visible. It can only be detected by careful measurement of the relative refringence at different points in a glass plate; this measurement is commonly made by means of an interferometer or a precision refractometer. A gradual change in refractivity in a lens or prism gives rise to an unequal warping of the transmitted wave surfaces and spoils the definition in the image.

Bubbles (*seeds, air bells, vacuum bubbles, boil*).[3]—At all stages in the melting and fining process of optical glass manufacture, volatile matter escapes from the melt; in case any of this volatile matter fails to reach the surface before the molten glass cools down, it remains entrapped in the melt as a bubble. (Fig. 8*a*.) Bubbles vary greatly in size from minute specks hardly discernible to the unaided eye to large bubbles several millimeters and even centimeters in diameter. Illuminated from the side by a strong source of light the bubbles in a piece of glass appear as brightly shining points or stars within the glass mass. Bubbles are not desirable in optical glass; but the effect of a bubble depends largely on its position within the optical system. A bubble is not tolerated in the image plane of a telescope system because it may disturb details in the field of view; but bubbles situated in lenses and prisms distant from the image plane are not in general serious, as they tend chiefly to cut out a negligible percentage of the transmitted light. Bubbles in a telescope objective are imaged in or near the exit pupil of the instrument; if they are large the effect on the observer's eye is the same as though a fine speck of opaque substance were actually placed directly in front of his eye; this holds true for striæ to a much greater degree. In most cases the bubbles are so small that this effect is negligible. In some instances a small bubble marks the position of a former particle of

[3] "Seeds" are small bubbles; "boil" are large bubbles developed toward the end of the fining period or as a result of "blocking"; "vacuum bubbles" are commonly of fair size and develop during the cooling down of the melt; "air bells" are of irregular shape and are formed generally during the pressing or molding operations.

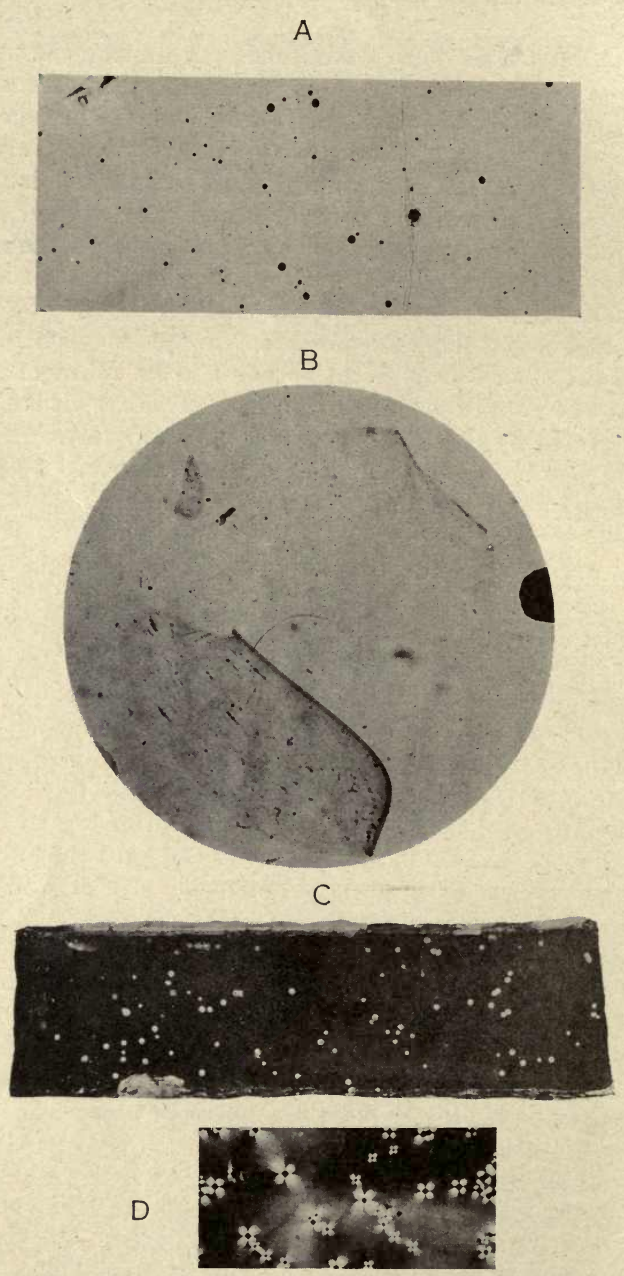

FIG. 8.—(*a*) Bubbles in a plate of glass; stone with striæ streamer near center of plate. (*b*) Pressing defects or "feathers" or "laps" in a lens. (*c*) "Stones" in optical glass; radial spherulites of cristobalite. (*d*) Part of specimen *c* in polarized light; shows strain-aureole around each stone.

sand or clay which, on solution, set free included gases, thus forming a small bubble. In this case the bubble is apt to mark the end of the short streak or stria in the glass which, if appreciably developed, is a sufficient cause for rejection of the glass. Optical glass should be free from bubbles of this nature.

Bubbles are not always easy to avoid entirely; and in some types of optical glass it is practically impossible to produce glass free from small seeds.

Stones.—Stones are included fragments of undissolved material in the glass mass. They may represent coarse particles of the original batch materials (batch stones, such as clusters of sand grains) which failed to be entirely dissolved during the glass-melting operation; more commonly they are pieces of the pot walls (pot stones) which, loosened from the sides or bottom of the pot, find their way into the melt. (Fig. 9*a*.) They may be fragments of the crown of the furnace (crown drops) which have fallen into the melt. Inclusions of any kind are unwelcome guests. The glass adjacent to them is usually in a state of great strain as a result of the difference in rate of contraction between glass and inclusion on cooling; characteristic cone-shaped fracture surfaces may develop in the glass adjacent to such inclusions.

Stones and included folds (feathers, pressing defects) of dusty material in lenses and prisms may be introduced during the pressing process after the glass has been taken into work. (Fig. 9*b*.) In preparing the glass fragments for pressing into desired shapes it is common practice for the workman to heat them up in a muffle furnace on a slab of refractory material. In order to prevent the softened glass from sticking to the plate during this operation, powdered clay, mica, talcum, graphite, or a mixture of these or other materials is spread over the plate. This powder clings to the undersurface of the softened glass fragments. In preparing each glass fragment for his press, the workman paddles it up into a suitable shape. If this operation is done carelessly, he plasters the sides of the fragments with the powder; in the pressing operation these dusty surfaces may be enfolded into the lens or prism blank (fig. 8*b*), thereby spoiling it for use in an optical system. Carelessness in this operation may result in large rejections of the finished blanks. Trouble from this source can be greatly reduced by the use of proper refractory base plates and by avoiding the use of excess powder. It is also possible to modify the procedure so that no powder is used and pressing defects are largely eliminated.

The presence of stones in optical glass is adequate cause for its rejection, because not only are they not tolerated in optical systems, but, as a result of solution, they commonly leave a trail of striæ in their passage to and fro in the melt, thus spoiling a much larger percentage of glass than their presence at isolated points within the glass mass might indicate.

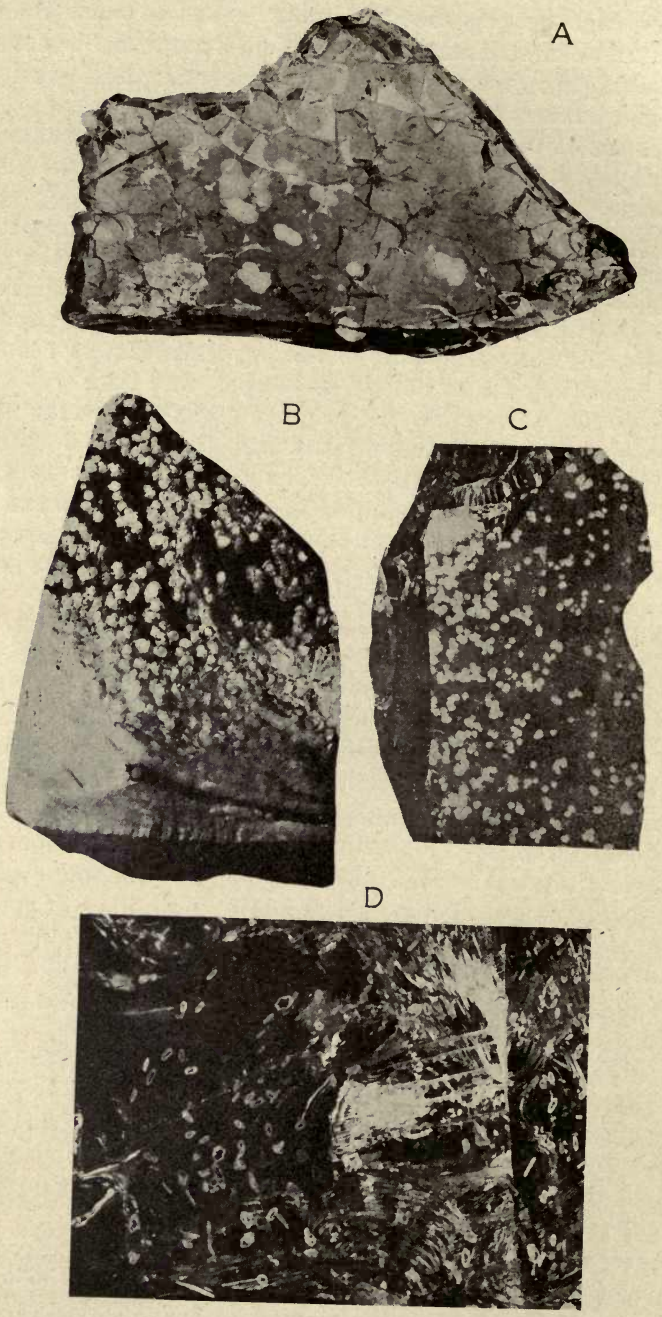

FIG. 9.—(*a*) "Stones" (spherulites of wollastonite) in glass; note also "joint" cracks developed on rapid cooling of the plate of glass. (*b*) Crystallization bodies in optical glass. (*c*) Spherulites of cristobalite on surface of barium crown melt. (*d*) Crystals of barium disilicate in barium crown glass.

Crystallization bodies. (radial spherulites, crystallites, devitrification stones).—On cooling down from a high temperature optical glass behaves like any other solution with falling temperature; the solution becomes supersaturated with respect to certain components and these begin to crystallize out if given time to do so. (Fig. 9a to d.) The homogeneity of the glass melt is thus destroyed; strains of appreciable magnitude are set up in the cooling glass mass adjacent to the crystallites and render it useless for optical purposes. (Fig. 8d.) The presence, in a lens or prism, of an inclusion, however small, is sufficient cause for its rejection.

Cloudiness.—Under certain conditions of manufacture cloudy or milky glass results. Turbidity or opalescence of this kind in optical glass is a very serious defect and renders it useless for optical purposes. The turbidity is easily detected and the glass is rejected before it passes beyond the first melting stage or at worst the lens- and prism-pressing stage of the manufacturing processes.

b. UNIFORMITY IN PHYSICAL STATE.

Freedom from strain.—Although a piece of glass may be homogeneous in a chemical sense, yet as a result of improper heat treatment it may be in a state of internal strain. This is to be avoided in optical glass chiefly for one reason. Glass under strain is not in eqiulibrium; and even at room temperature the internal stresses seek relief by slow movement within the glass block. In a highly strained piece of glass the internal movement may reach some mechanically weak spot in the glass mass, such as a stria or an inclusion that is not able to maintain the stress; the result is then a rapid shearing and consequent fracture. The glass plate or lens cracks without warning. The movement of the strain over portions of a piece of glass is readily followed by examination in polarized light. In optical systems lenses and prisms of definite shapes and sizes are used. A slight departure from the prescribed surfaces gives rise to defects in the image which are readily detected and impair its quality. Strain in optical glass causes the surfaces to warp during the polishing and figuring processes. This tendency toward deformation continues after the several elements of an optical system have been mounted and is a constant source of trouble to the extent of causing an element to crack and thus to render the whole optical system useless.

A piece of glass under strain is analogous, in its behavior toward transmitted light waves, to a birefracting crystal. This was discovered in 1813 by Sir David Brewster[5] who found that a glass plate under load (compressional stress) behaves as a uniaxial negative crystal, the optic axis being the direction of application of the load.

[4] The identification of stones in optical glass is discussed by N. L. Bowen in J. Amer. Ceramic Soc., I, 594–605, 1918.

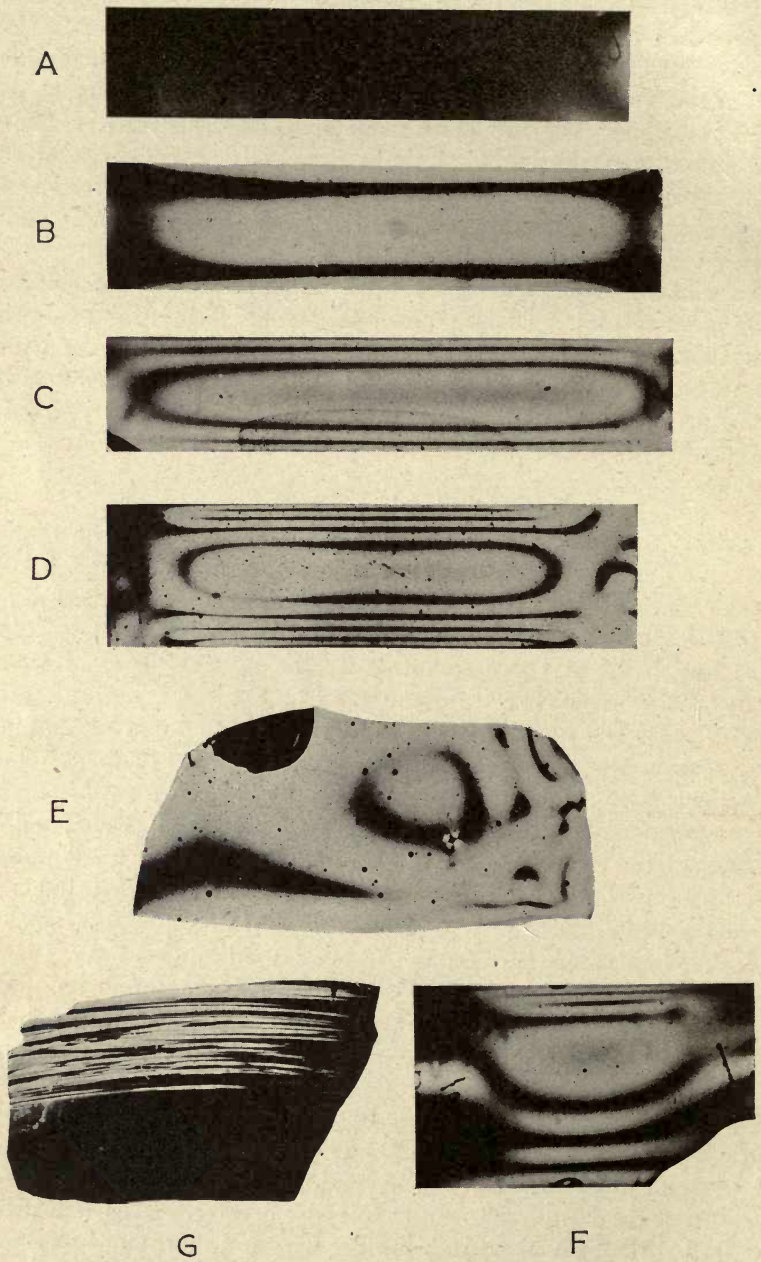

FIG. 10.—(*a*) Well-annealed piece of optical glass. (*b*) Annealing fair. (*c*) Annealing poor; note pressing defect in lower half of plate. (*d*) Annealing very poor. (*e*) Annealing poor in piece of optical glass; note that bubbles (black spots) show no evidence of local strain, whereas the stone to the right of the center of the piece exhibits pronounced local strain. (*f*) Heavy striæ cause strain in a well annealed block of glass. (*g*) Poorly annealed block of glass.

Brewster discovered that the degree of birefringence, as measured by the path difference of the two plane-polarized light waves formed on traversing the strained block at right angles to the direction of the applied load, is proportional to the load itself; in other words the path-difference per unit length of path or the birefringence may serve as a direct measure of the strain.

It may be inferred that because two rays of different refractive indices are formed as a result of the strain these may seriously affect the quality of the image. In order to test out this inference the degrees of strain in a number of plates of different types of optical glass made by Schott & Genossen, by Parra-Mantois, and by glass-makers in this country were measured. On each plate the actual maximal path difference between the transmitted light waves was determined and this in turn was reduced to path difference per centimeter length of glass path traversed. (Fig. 10.) In the best annealed samples the maximal observed path difference for sodium light at the margin of the glass plate was less than 5 millimicrons (millionths of a millimeter) per centimeter glass path. In optical glass of fair quality the path difference reached a value of 20 millimicrons per centimeter; in samples of poor quality a path difference of 40 to 50 millimicrons per centimeter was reached. But even a path difference of 50 millimicrons per centimeter is equivalent to a difference of only 0.000005 between the refractive indices of the two transmitted waves; this difference is negligible even in the best optical systems. Experience has shown that a difference five times this value is within the tolerance limits of the most exacting optical systems.

There is still a possibility to consider, namely, the change in refractive index of the material under hydrostatic pressure and the change in actual refractive indices for rays vibrating parallel and normal to the direction of an applied load. Measurements by Kerr,[6] Pockels,[7] and computations by Adams and Williamson [8] have shown that the index of refraction of glass is increased by compressional load and decreased by tensional load. Kerr found from measurements with a Jamin interference refractor that in the case of compression both waves are retarded, while in the case of tension both waves are accelerated; that the wave whose vibrations take place in the plane normal to the direction of the applied load is retarded most, its retardation being practically twice that of the wave vibrating along the axis of pressure.

S. Czapski [9] measured the relative and absolute changes in refractive index in poorly annealed glass rods and plates by a dioptric

[5] Philosophical Transactions, 1814, 1815, 1816.
[6] J. D. Kerr, Phil. Mag. (5), **26**, p. 321, 1888.
[7] F. Pockels, Ann. d. Phys. (4), **7**, p. 745, 1902.
[8] L. H. Adams and E. D. Williamson, Jour. Wash. Acad. Sci., **9**, pp. 609-623, 1919.
[9] S. Czapski, Ann. d. Phys. u. Chem., **42**, p. 319, 1891.

method based on Brewster's and Exner's observation that a cylindrical glass rod behaves optically as a meniscus lens. Czapski found that the index of refraction for both waves increases from the center of the glass rod or plate; for crown glass, so strained that the resulting path difference is about 400 millimicrons per centimeter, the increase in refractive index of the wave vibrating parallel with the axis of pressure is 0.0000914 and for the second wave 0.0000468; for a second plate, so strained that the resulting path difference is about 150 millimicrons per centimeter, the increases in refractive indices are 0.0000303 and 0.0000155, respectively; for a flint block so strained that the path difference is about 325 millimicrons per centimeter, the increases in refractive indices were 0.0001465 and 0.0001166, respectively.

Adams and Williamson ascertained by computation that the index of refraction of a light flint glass of refractive index $n_D = 1.57$, is increased 0.00118 by hydrostatic pressure of 1,000 kilograms per square centimeter; that in the case of a load of 1,000 kilograms per square centimeter (undirectional pressure) the increases in refractive indices of the two waves vibrating normal and parallel with the axis of pressure are, respectively, 0.00049 and 0.00020. Their experimental results show, moreover, that the birefringence resulting from the application of a load of 1 kilogram per square centimeter to a block of glass ranges from 2.5×10^{-7} to 3.2×10^{-7} for the ordinary types of glass. The observation by Brewster that the optical effect produced is directly proportional to the amount of the stress was also found by them to be valid. For extra dense flints and dense barium crowns these birefringence values decrease perceptibly, so that for a very dense flint containing about 74.0 per cent PbO the birefringence is zero irrespective of the state of annealing. This conclusion is in accord with that first reached by Pockels from measurements with a Jamin differential refractor.

The foregoing results by Adams and Williamson are larger than, but of the same order of magnitude as those obtained by Czapski. They show that a strain birefringence of 10×10^{-6} (path difference of 10 millimicrons per centimeter), which is about the limit permissible in good quality optical glass, is produced by a load of 40 kilograms per square centimeter and that for this load the change in refractive index of the light flint for the wave vibrating normal to the axis of pressure is 0.000016 or at most 2 in the fifth decimal place, a negligible amount in its optical effect on the quality of the image. In the case of a large telescope objective improperly supported so that its weight is held at a few isolated points, the pressure at these points may greatly exceed 40 kilograms per square centimeter and a serious amount of strain be thereby introduced.

Direct measurements of the change in refractive index of strained glass as compared with that of the same piece after annealing were first made by Schott[10] and later by Czapski[11] who found differences in refractive index up to 0.003, the refractive index of the well-annealed glass being invariably higher than that of the heavily strained glass. Similar series of measurements made at the Bausch & Lomb plant at Rochester with an Abbe-Pulfrich total refractometer led to the same results; the refractive index of a "proof" taken from a pot of molten glass was invariably lower, from 0.001 to 0.004 lower than that finally obtained on the well-annealed plates of glass from the same pot. The same order of magnitude for the effect of strain was obtained at the plant of the Pittsburgh Plate Glass Co. at Charleroi, Pa., on "dips" or "proofs." For the measurements refractive liquids of known refractive index were employed; the "dip" of glass was immersed in a tank of refractive liquid and its refringence was compared directly with that of the liquid and a standard glass sample.

The foregoing measurements demonstrate clearly that the chief effect of strain in optical glass is to deform and warp the optical surfaces. Strained glass is not in a state of equilibrium; relief from the internal stresses is sought by internal differential movements. Experience has proved that even at room temperatures prisms and lenses made of strained glass do not retain their shape satisfactorily; with the oscillations of room temperature, the accurately wrought surfaces of the prisms and lenses undergo constant warping and change; these changes are very slight, but in high precision instruments they are sufficient to render such an optical element useless. If the maximum path difference resulting from strain exceeds 20 millimicrons per centimeter glass path there is danger of surface warping and consequent introduction of astigmatism and other defects in the image. If the strain is uniformly distributed, this defect can be overcome to some extent; but if the strain distribution is irregular, there is no method for counteracting its damaging effect on the quality of the image. Hence the importance of proper annealing of optical glass. No glass is entirely free from strain, but if the greatest strain in a plate of optical glass is below a certain limit (resulting maximum path difference less than 5 millimicrons per centimeter glass path) the tendency toward warping of polished glass surfaces is practically nil.

REFRACTIVITY.

The function of the lenses and prisms in an optical instrument is to change the directions of propagation of incident light waves so that when they reach the eye of the observer and produce an image on

[10] Zeitschrift Instrumentenkunde, *10*, 41, 1890.
[11] Ann. d. Phys. (4) 7, 330, 1902.

the retina, this image has the desired qualities. This change in the paths of light waves is made possible by the fact that on traversing different substances light waves encounter different degrees of resistance depending not only on the substance, but also on the color of the light itself (wave length). A measure for the relative rate of travel of a light wave of given color through a substance is the reciprocal of the refractive index. The refractive index of a substance is in fact the ratio between the velocity of light in free space (vacuum) to that in the substance. Light waves of different color travel at different speeds through a substance (fig. 11*a*); as a result, a beam of white light is resolved into its colored components by a prism, the blue rays being deflected the most, the red rays the least (fig. 11*b*); the emerging rays are deflected or dispersed in a definite order

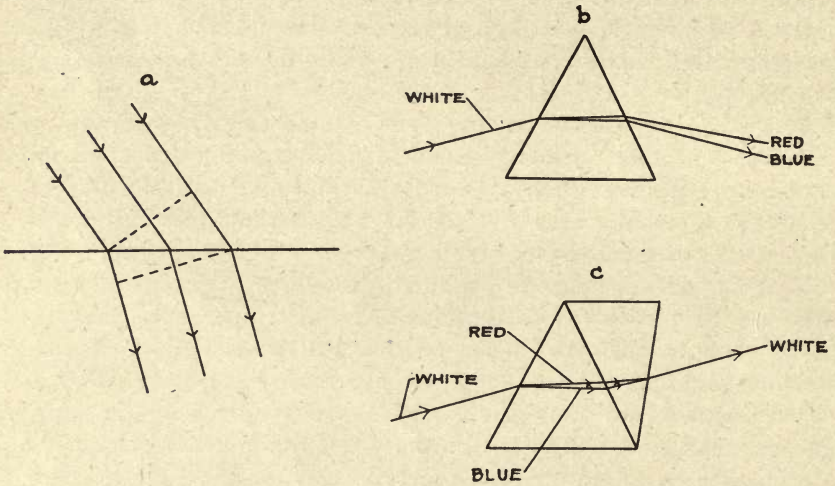

FIG. 11.—(*a*) Refraction of plane-parallel light at a plane surface. (*b*) Dispersion of white light in a prism. (*c*) Achromatic prism pair.

(spectrum). The amount of this deflection, both actual and relative, depends on the refracting substance. Different optical glasses behave differently in this respect; the refractivity of an optical glass is ordinarily specified by its refractive indices for certain definite colors or lines of the spectrum. The spectral lines commonly chosen are A', C, D, F, G' of the solar spectrum and have respectively the wave lengths: 0.7682, 0.6563, 0.5893, 0.4862, and 0.4341 microns (thousandths of a millimeter).

In lists of optical glass it is customary for the manufacturer to state the refractive index for the mean of the two D lines only, and to give the differences in refractive indices between the D and C lines, between F and D, between G' and F, between D and A', and between F and C. These differences are measures for the dispersion of the glass in the different parts of the spectrum and suffice to characterize its type.

A derived value, namely, the ratio $\frac{n_F - n_D}{n_F - n_C}$ between the difference in the refractive indices for any two spectral lines, as for example, n_F and n_D, and the difference, $n_F - n_C$, in refractive indices for the two spectral lines F and C, is called a *partial dispersion ratio.* The partial dispersion ratios are a measure of the relative lengths of the partial spectra in the different glasses. The differences between the partial dispersion ratios of two glasses express the degree of similarity of their spectra. A second derived value, introduced by Abbe, is in general use and is commonly designated by the Greek letter ν. It has been called the *optical constringence,* and is the ratio of the refractive index for the D line (sodium light) minus one (effective or excess refractivity) to the difference between the refractive indices for the F and C lines (mean dispersion); its reciprocal is a measure of the dispersive power of the glass. In other words the quantity $\nu = \frac{n_D - 1}{n_F - n_C}$ expresses the effective refractivity as measured in terms of the mean dispersion; its reciprocal expresses the mean dispersion in terms of the effective refractivity.

To correct for color dispersion and yet to obtain the desired deflection of the light rays the lens designer combines an optical glass of weak dispersion with one of high dispersion; thus in a single prism (fig. 11*b*) the rays on emerging from the prism are dispersed at different angles and a beam of white light is thereby resolved into its colored components such that a spectrum is formed; in an achromatic prism combination, however (fig 11*c*), the dispersion of the first prism is neutralized by that of the second with the result that the incident pencil of light is deflected but emerges as a beam of white light. The spectra produced by the two prisms are superimposed in reversed order so that the dispersing effect of the first glass is neutralized by that of the second. In order that this superposition of spectra be effective, it is obviously necessary that the relative dispersions in the two glasses be the same. If in the first prism the red end of the spectrum is drawn out relatively to the blue, while in the second the blue end extends over a greater relative range than in the first, the superimposed spectra can not be made to fit, and a considerable amount of residual color will be left in the emergent beam.

In lenses the designer brings together to the same focus rays of one or more colors; he folds the spectrum over, as it were; this procedure is successful to the degree that the relative dispersions in the two glasses of the achromatic objective are similar; to the extent that they are dissimilar there is residual color (secondary spectrum) in the image which can not be eliminated. It is evident that two glasses produce a combination the better adapted for achromatizing,

the less their partial dispersion ratios differ and the more the glasses differ in effective refractivity as expressed in terms of the mean dispersion (ν value). It can be proved that the differences in focal length of a telescope objective lens for the different colors in the spectrum decrease with decrease in difference between the partial dispersion ratios and increase with decrease in difference between the ν values of the two glasses. In other words, two glasses are the better fitted for achromatizing the more nearly equal are their partial dispersion ratios and the greater the difference in their ν values. It can also be shown that the sum of the curvatures of each lens decreases with increase in difference between the ν values.

By combining lens elements of optical glasses of different refractive indices and dispersions it is possible for the designer to obtain much more perfect images and optical performance than with single lenses. In the older types of optical glass, ordinary crowns and ordinary flints, the lead in the flint glasses dominates the optical behavior of the glass with respect both to refractive index and to dispersions, so that in the series of flint glasses the ratio between refractive index and dispersions is practically linear, the dispersion increasing in direct proportion with the refractive index for any given spectral line. This relation between refractive index and dispersion was used to advantage by lens designers to produce images of fair quality; but it also set a limit to the possibilities of results that could be obtained, and experience showed that under such conditions it was impossible to attain the degree of correction required for more exacting lens systems. If these were to be realized it was necessary that new glasses of different relations between refractivity and dispersion be produced.

The task of obtaining glasses of the desired refractivities and dispersion ratios involves the study of the effects which changes in chemical composition produce on the optical constants of the finished optical glass. The oxides which were used half a century ago in glass manufacture were few and included chiefly the oxides of silica, sodium, potassium, calcium, lead, and aluminium. The first attempts to introduce other elements into glass for the purpose of modifying the optical properties were made by Harcourt,[12] in England, between 1834 and 1860 in collaboration with Stokes; he discovered the effects exerted by boron and barium on the optical constants of glass; his experiments were on a small scale only and did not lead to the commercial production of such glasses.

In 1880 and the following years detailed studies were made by Schott and Abbe, in Jena, Germany, where, with the financial aid of the Government, a number of new types of optical glass were produced commercially for the first time. Schott introduced ele-

[12] Report of the British Association for the Advancement of Science, 1871, 1874.

ments, such as boron (as oxide and borates), phosphorus (as phosphates), barium (as carbonate or oxide), fluorine (as a fluoride), and felt assured of a certain degree of success in obtaining glasses of the desired optical qualities because these elements occur in nature in crystallized compounds, which are characterized optically by extremes in refractivity and dispersion. These extremes have never been attained by optical glasses; there is, moreover, no prospect of producing glasses of these properties chiefly because of the crystallizing tendencies of melts of such abnormal compositions. These melts can not be chilled with sufficient rapidity on a commercial scale to prevent their crystallization. Glasses of other abnormal compositions may not exhibit this tendency to crystallize, but the final product may be chemically unstable, so that the glass is readily attacked by the atmosphere and even by the materials used in the grinding and polishing processes; or the finished glass may be so soft as to be of little service in optical instruments. Glasses of these abnormal compositions showing extremes in refractivity or in dispersion are always difficult to manufacture; they tend not only to crystallize or to be chemically unstable, but they are prone to attack the glass pot and to develop other troubles, such as bubbles, which are difficult to overcome on a large scale in the factory.

The studies undertaken by Schott and Abbe for the purpose of obtaining new types of optical glass extended over a period of years. These investigators developed a number of new types of optical glass in which the dispersion ratios of certain pairs were more nearly in accord than were those of the older glasses. With the new types of optical glass much better color correction can be obtained in optical lens systems. Their new types of glass include the series of borosilicate crowns, of barium crowns, of barium flints, borate flints, the borate and phosphate glasses. In these glasses the character of the dispersion varies from type to type.

We shall now consider in some detail and by means chiefly of graphical plots the dispersion relations in optical glasses in order to gain deeper insight into the significance of dispersion in optical glasses and its change with change in chemical composition.

A fundamental requirement of optical glass is transparency and freedom from color; this means the absence of an absorption band in the visible spectrum; and this in turn sets a definite limitation to the possible variations in refractivity and greatly restricts the general character of the dispersion relations. With change in color (wave length of light) the refractive indices of optical glass change in the manner illustrated in figures 12*a* and 12*b*, in which the refractive indices of different kinds of optical glass [13] are plotted for different wave lengths

[13] Measured by H. Rubens and H. T. Simon on a series of Schott glasses. Ann. d. Phys. u. Chem. N. F., 53, 555, 1894.

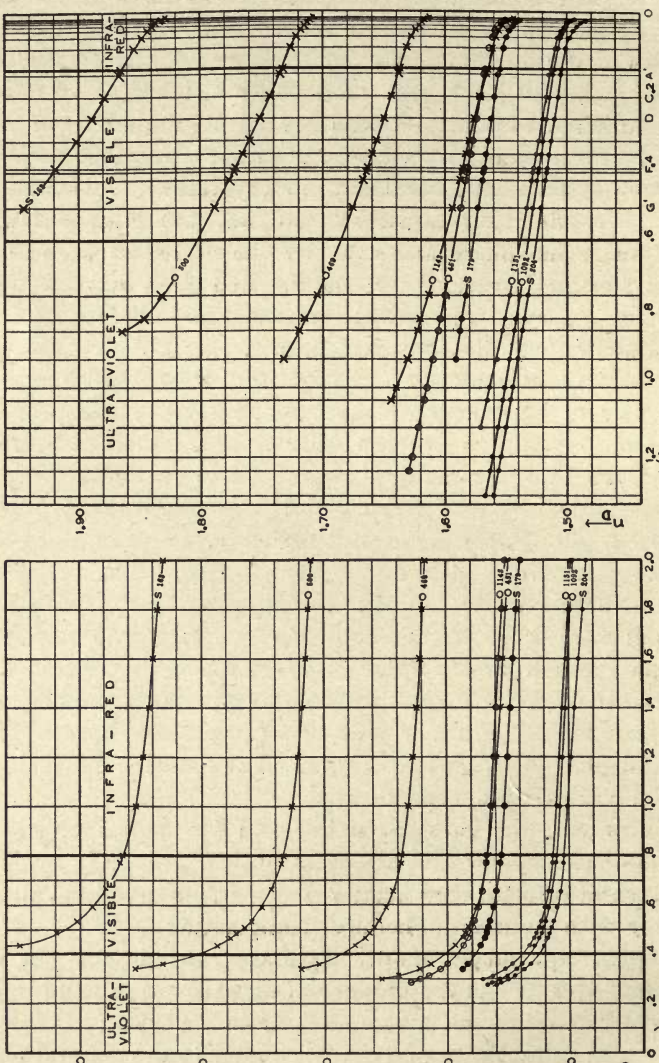

FIG. 12.—(*a*) In this figure the refractive indices for different wave lengths in the infra-red, visible, and ultra-violet, as measured by H. Rubens and H. T. Simon on a series of Schott glasses, are plotted as ordinates against the wave lengths as abscissæ. (*b*) In this figure the abscissæ scale has been changed from the direct wave-length scale (λ) of fig. 12a to that of the square of the frequency ($1/\lambda^2$). The refractive indices are the ordinates. By this method of plotting, the inflection point of the dispersion curves in the visible spectrum is clearly shown as a result of the absorption band in the ultra-violet and also in the infra-red.

of light extending from the ultra-violet through the visible spectrum into the infra-red. In figure 12*a* the refractive indices (ordinates) are plotted against the wave lengths, λ, directly (abscissae); in figure 12*b* the refractive indices are plotted against the squares of the recip-

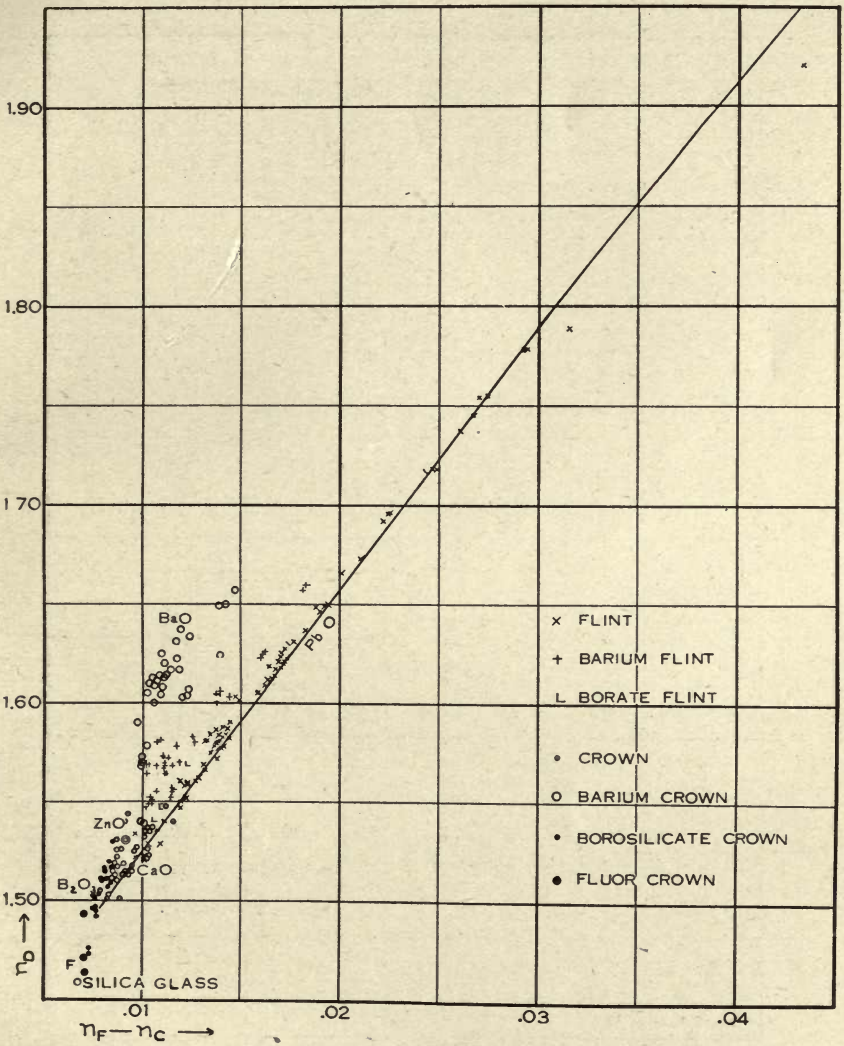

FIG. 13.—In this figure the mean dispersions, $n_F - n_C$, of a series of different types of silicate optical glasses are plotted against the refractive indices, n_D. The points of projection for the ordinary crowns and the ordinary flints fall on a practically straight line, as indicated in the diagram.

ls of the wave lengths ($1/\lambda^2$, frequency squared). The glasses represented in figures 12*a* and *b* include the old types of ordinary crowns and flints and also barium crowns, flints, and borate glass; thus S 204 is a borate glass ($n_D = 1.51007$, $\nu = 58.8$); O 1092, a light barium crown ($n_D = 1.57698$, $\nu = 62.0$); O 1151, a crown of high dispersion

($n_D = 1.52002$, $\nu = 51.8$); S 179, a phosphate crown ($n_D = 1.56207$, $\nu = 67.2$); O 561, a light flint ($n_D = 1.57524$, $\nu = 41.2$); O 1143, a barium crown ($n_D = 1.57422$, $\nu = 57.1$); O 469, a dense flint ($n_D = 1.64985$, $\nu = 33.7$); O 500, an extradense flint ($n_D = 1.75130$, $\nu = 27.6$); S 163 densest flint ($n_D = 1.88995$, $\nu = 22.3$).

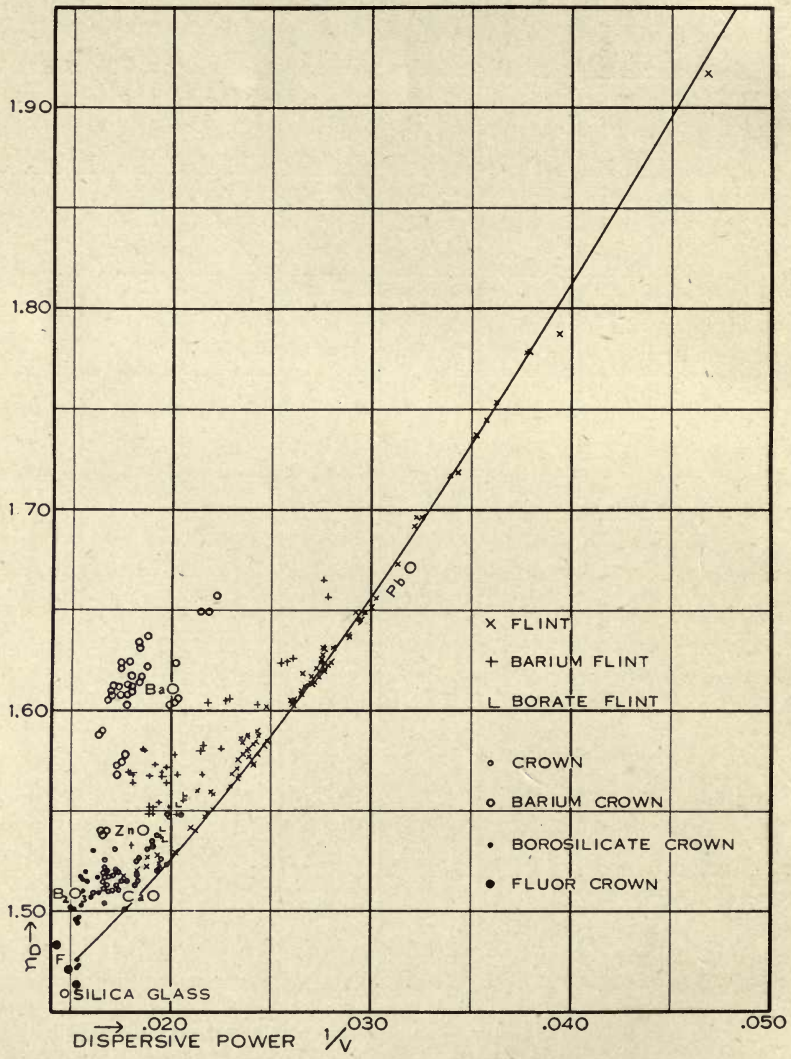

FIG. 14.—In this diagram the dispersive powers of a series of optical glasses are plotted against their refractive indices, n_D.

It may be noted that the dispersion curves of figure 12*b* show an inflection point in the visible spectrum; as a result, the run of dispersions throughout the visible spectrum is represented by approximately straight lines in the different glasses. These relations have an

important bearing on the development of certain dispersion formulas and will be discussed in a later paragraph.

In the old types of glasses (ordinary crowns and ordinary flints) the dispersion increases with the refractive index (figs. 13 and 14); but the dispersion in the blue end of the spectrum increases more rapidly than that in the red and the spectra of different glasses are so dissimilar (irrationality of dispersions) that only a fair correction for achromatism can be attained. The introduction of new types of glasses by Abbe and Schott enabled the lens designer to produce much better lens systems than was formerly possible.

It has long been known that if the mean dispersions of ordinary crown glasses and of flint glasses be plotted against refractive index the points fall approximately on a straight line (fig. 13). In other words, in these older types of glass the mean dispersion increases directly with the refractive index. It was to overcome this limitation that Harcourt, and later Abbe and Schott, investigated the changes produced in optical glasses by radical changes in the chemical composition. They found that boron and barium are especially valuable in this connection; in figure 13 the relations between refractive index and mean dispersion in the new Schott and Parra-Mantois glasses are also given and show how far some of these depart from the straight line of the old flints and crowns.

If the dispersive powers ($1/\nu$ as defined above) of the Schott glasses are plotted against the refractive index (fig. 14), the old-type glasses fall on a slightly curved line; the fields of the new types of glasses are clearly differentiated on the diagram. This is also true when the ν-values of the glasses are plotted against refractive index, although in that diagram the curve of the old-type glasses is much more curved.

In figure 15 the ratios of the partial dispersions in the red ($n_D - n_A'$) and blue ($n_G' - n_F$) ends of the spectrum (relative length of the red to that of the blue) are plotted against the refractive index, n_D. This diagram illustrates probably better than the others the refractivity-dispersion relations; in it the fields of the different glass types are well marked. Thus in the fluor-crown glasses the length of the red end of the spectrum exceeds that of the blue end relatively more than in any other glass type; the borosilicate crowns follow next in order; then the ordinary crowns, the barium crowns, the barium flints, and finally the flints in which the relative dispersion of the blue ($n_G' - n_F$) exceeds that of the red ($n_D - n_A'$).

It is possible from figure 15 to select glasses differing appreciably in absolute refringence and at the same time to state their relative dispersions in the blue and red parts of the spectrum. Chemical analyses of many of the glasses plotted on this diagram are listed in Table 4 (p. 59); by combining graphically the information presented in figure 15 and Table 4 it is possible to deduce by interpola-

tion the approximate chemical compositions of glasses intermediate in optical properties between those which are plotted. The methods for accomplishing this are described in a later paragraph. Figure 15

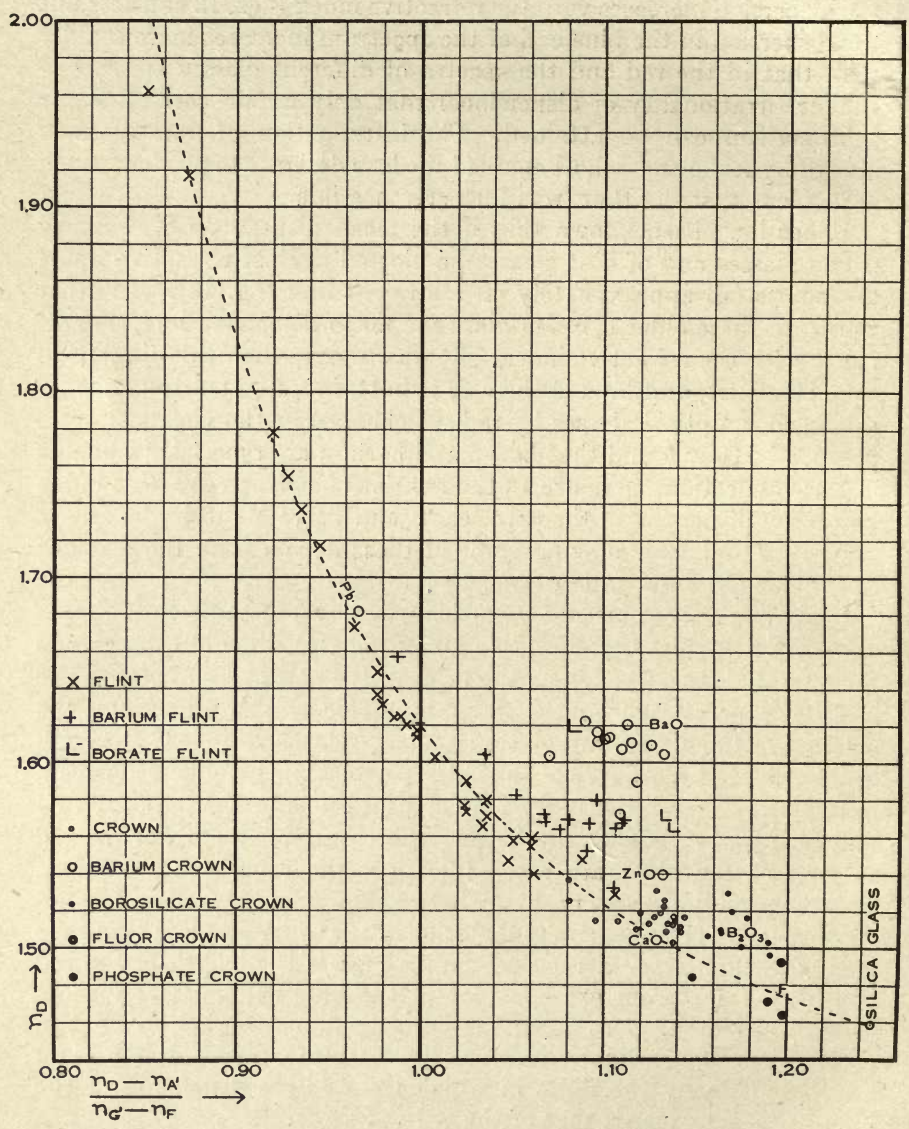

FIG. 15.—In this figure the ratio $(n_D - n_{A'})/(n_{G'} - n_F)$, which expresses in effect the length of the red end of the spectrum to that of the blue end, is plotted against the refractive index n_D for a series of different types of silicate optical glasses.

shows, moreover, the extent to which the glassmaker has succeeded in changing the refractivities of optical glasses. The diagram includes the borate and phosphate glasses in addition to the silicate glasses.

If now we consider only the partial dispersions and plot, as in figure 16, the partial dispersion $n_F - n_C$, $n_F - n_D$ and $n_G' - n_F$ against $n_D - n_A'$ for a series of silicate glasses, the result in each case is a straight line; in figure 16 the partial dispersions of all the silicate glasses listed by Schott of Jena, and by Parra-Mantois of Paris (about 289 different glasses in all) are included except those of the densest

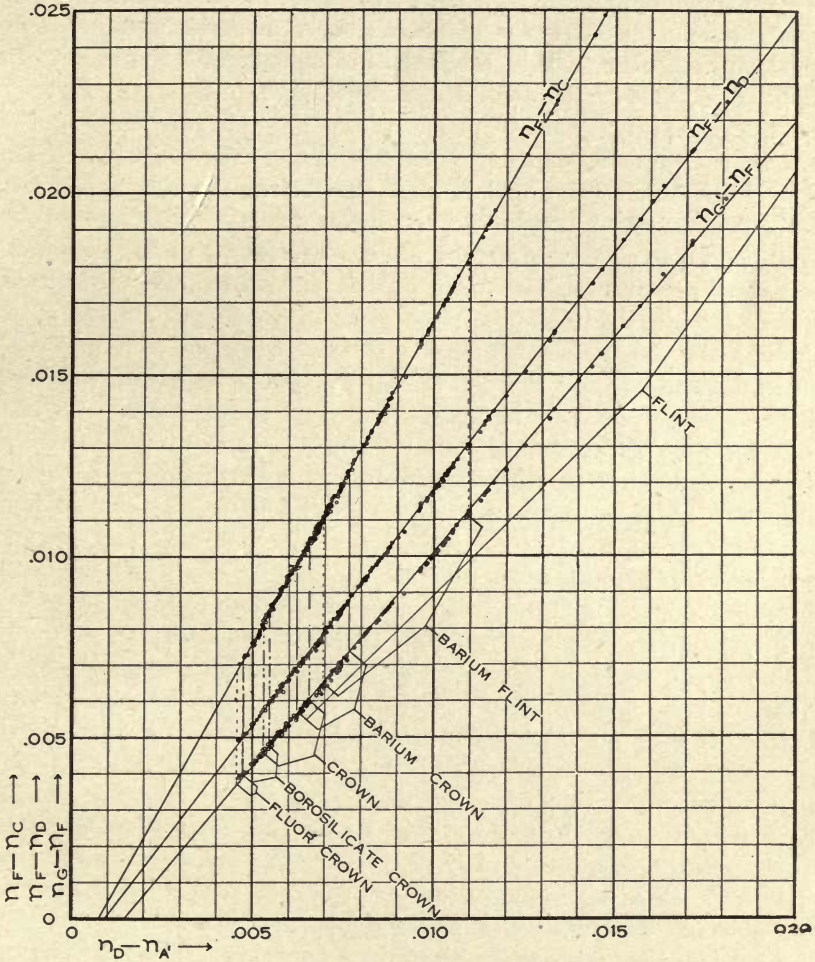

FIG. 16.—In this figure the partial dispersions, $n_F - n_D$ and $n_G' - n_F$ of all silicate optical glasses listed by Parra-Mantois and by Schott, are plotted as ordinates against the partial dispersion $n_D - n_A'$ as abscissæ. The result in each case is a straight line.

flint S 386 of Schott. This is a remarkable result and states that any partial dispersion of a glass bears a linear relation to any other partial dispersion; the degree of departure from this relation does not exceed one or two units in the fourth decimal place for the glasses plotted. Except for the dense barium crown glasses the dis-

tance of the points from the straight line is commonly only a few units in the fifth decimal place.

This fact, that in a series of optical glasses the partial dispersions are related by linear functions, proves that once a partial dispersion is given, the entire dispersion curve is fixed irrespective of the type of optical glass. This means that within the limits to which this statement holds, namely, one or two units in the fourth decimal place, if any partial dispersion is given, all other dispersions follow automatically; in other words, a change in dispersion at one part of the dispersion curve carries with it definite changes in the curve throughout the visible spectrum. Thus a series of standard dispersion curves can be set up independent of the absolute refractive index. This signifies that if, for any optical glass, two refractive indices be given, its dispersion curve can be written down directly; that in case two optical glasses of very different indices are found to have the same actual dispersion for one part of the spectrum, their dispersion curves are identical to one or two units in the fourth decimal place throughout the visible spectrum. If, for example, the refractive index n_D, and the ν value of an optical glass be given, its mean dispersion, $n_F - n_C$, can be computed from the equation $n_F - n_C = (n_D - 1)/\nu$; its partial dispersions $n_D - n_A'$, $n_F - n_D$, and $n_G' - n_F$ can then be read off directly from figure 16 with a fair degree of accuracy, sufficient, at least, to give an adequate idea of the run of dispersion in the glass.

From these relations it is possible to build up empirical dispersion formulas containing two or three constants which represent the data in the visible spectrum with a high degree of exactness.[14]

The linear relations between the partial dispersions of an optical glass are valid only for that portion of the dispersion curve which is distant from an absorption band. With the approach to an absorption band the dispersion curve departs from its even course and is no longer comparable with the dispersion curves of other glasses. This is well shown in figure 17 in which the measurements of H. Rubens in the infra-red and H. T. Simon [15] in the visible and ultra-violet of a series of optical glasses are plotted in terms of the partial dispersions. The different types of glasses are named on the diagram and are identical with those plotted on figure 12. The similarity in the course of the partial dispersions is well shown by two glasses in the list, namely, a crown of high dispersion, O 1151, of refractive index $n_D = 1.52002$, and a barium crown, O 1143, of refractive index $n_D = 1.57422$. In Table 2 the partial dispersions $n_r - n_D$ are listed. In this table it is evident that the partial dispersions of the two glasses run along fairly well together from the infra-red at 2 μ to the

[14] F. E. Wright. Journ. Opt. Soc. America, IV, 148–159, 1920.
[15] Ann. Phys. u. Chem. N. F. 53, 555, 1894.

violet of the visible spectrum. From here on into the ultra-violet the crown with high dispersion, which contains 13.3 per cent of lead

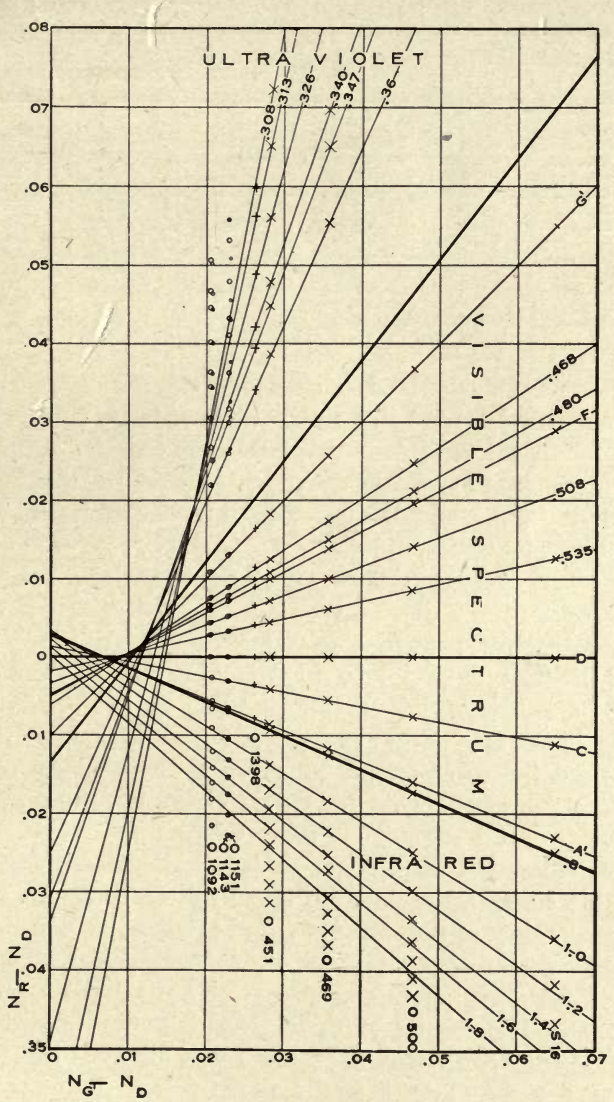

FIG. 17.—In this figure the partial dispersions $n_r - n_D$ between the sodium line and the following wave lengths in microns: 2.4, 2.2, 2.0, 1.8, 1.6, 1.4, 1.2, 1.0, 0.8, 0.7682, 0.6563, 0.5892, 0.5349, 0.5086, 0.4861, 0.4800, 0.4678, 0.4340, 0.3610, 0.3466, 0.3403, 0.3261, 0.3133, 0.3081, 0.2980, 0.2880, 0.2837, 0.2763, are plotted as ordinates against the partial dispersions, $n_{G'} - n_D$, for a series of optical glasses measured by H. Rubens and H. T. Simon. The partial dispersions of the following Schott optical glasses are plotted on the diagram: O 1092, light barium crown, (n_D=1.51698); S 204, borate glass, (n_D=1.51007); O 1143, dense barium crown, (n_D=1.57422); O 1151, crown of high dispersion, (n_D=1.52002); O 451, light flint, (n_D=1.57524); O 469, dense flint, (n_D=1.64985); O 500 dense flint, (n_D=1.75130); S 163, extra dense flint, (n_D=1.88995).

oxide, approaches an absorption band and its partial dispersions rise accordingly.

TABLE 2.

In this table the partial dispersions, $n_r - n_D$ of a crown of high dispersion, O 1151, and a barium crown, O 1143, are given for a series of wave lengths, r, extending from the infra-red at 2 μ to the ultra-violet at 0.2980 μ.

Wave length in μ.	O 1151. $n_r - n_D$.	O 1143. $n_r - n_D$.	Wave length in μ.	O 1151. $n_r - n_D$.	O 1143. $n_r - n_D$.
r			r		
2.0	−0.02272	−0.02272	0.4861	0.00713	0.00704
1.8	− .02012	− .02012	0.4800	.00780	.00766
1.6	− .01762	− .01772	0.4678	.00901	.00884
1.4	− .01522	− .01542	0.4340	.01310	.01288
1.2	− .01312	− .01312	0.3610	.02664	.02500
1.0	− .01042	− .01312	0.3466	.03066	.02977
0.8	− .00692	− .00692	0.3403	.03260	.03161
0.7682	− .00634	− .00640	0.3261	.03768	.03623
0.6563	− .00290	− .00302	0.3133	.04305	.04103
0.5892	.00000	.00000	0.3081	.04556	.04103
0.5349	.00325	.00324	0.2980	.05091	.04791
0.5086	.00523	.00516			

The different effects of lead, barium, boron, and other glass-making oxides are more clearly shown in the infra-red and ultra-violet than in the visible spectrum. The maximal departure from normal dispersion curves in the visible spectrum caused by the presence of large amounts of barium is approximately two units in the fourth decimal place.

In the series of flint glasses an increase in lead oxide content raises the refractive index and causes the absorption band in the ultra-violet to shift toward the visible spectrum. This is clearly shown by the flint glasses plotted in figure 12, namely O 451, O 469, O 500, S 163. Simon was unable, because of the presence of this absorption band, to measure the refractive indices of the light flint O 451 beyond the wave length 0.2980 μ, of the medium flint O 469 beyond 0.3261 μ, of the very dense flint O 500 beyond 0.3403 μ, and of the densest flint S 163 beyond 0.4340 μ.

Further evidence of the shift of the absorption band with increase in lead-oxide content has been obtained by the direct measurement of the transparency of the flint glasses in ultra-violet light. Data on the transmission of plates of flint and other optical glasses in the ultra-violet are given in the catalogue of optical glasses issued by Chance Bros. The results of their measurements on the flint and other glasses are reproduced in Table 3 in which the limit of transparency of a glass plate 1 centimeter thick is indicated by the wave lengths at which the percentage transmissions are 50 and 10 respectively.

TABLE 3.—*Transparency of flint and other glasses of Chance Bros. in the ultra-violet.*

Type No.	Name.	n_D.	ν	Approximate per centage PbO.	Wave lengths (μ) for transmission.	
					50 per cent.	10 per cent.
7863	Extra light flint	1.5290	51.6	18	330	321
6953	Light flint	1.5412	47.6	23.5	316	313
572	Dense flint	1.6182	36.4	45	337	330
360	.....do	1.6225	36.0	46	338	332
337	Very dense flint	1.6469	33.7	51	347	341
4480	.....do	1.7401	28.3	66	370	360
7423	Fluor crown	1.4785	70.2	.....	301	295
646	Borosilicate crown	1.5087	64.2	.....	315	309
1203	Hard crown	1.5155	60.8	.....	318	311
9322	.....do	1.5186	60.3	.....	315	309
1066	Zinc crown	1.5149	57.9	.....	323	312
569	Soft crown	1.5152	56.9	.....	314	309
3463	Light barium crown	1.5407	59.4	.....	309	307
9002	Medium barium crown	1.5744	57.9	.....	338	329
9753	Dense barium crown	1.5881	61.1	.....	358	353
4873	.....do	1.6118	59.0	.....	348	335
1453	.....do	1.6126	56.7	.....	350	339
5062	Light barium flint	1.5515	51.7	.....	323	320
7983	.....do	1.5534	46.1	.....	318	316
4277	Telescope flint	1.5250	51.7	.....	337	328

With the exception of the first member of this series, which may contain appreciable amounts of zinc or barium oxides that may affect the transparency in the ultra-violet, the absorption band shifts continuously with increase in lead content toward the longer wave lengths and the visible spectrum.

The yellow color of the very dense flints has been ascribed to the influence of this absorption band in reducing the intensity of the violet and blue of the visible spectrum; other factors, however, such as the presence of small amounts of iron oxide and possibly also of lead dioxide or other oxide of lead as impurities, may have a pronounced influence on the color. Very dense flint glasses made of materials of high chemical purity and under conditions of thorough oxidation are noticeably less colored than glasses of the same composition whose batches and heat treatment have not been scrutinized carefully.

There are other approximately straight-line dispersion relations within the visible spectrum which may be noted because on them certain empirical dispersion formulas are based. Thus if the refractive indices be plotted as ordinates against the squares of the frequency ($1/\lambda^2$) as abscissae, the course of the dispersion of an optical glass is represented by a curve which departs only slightly from a straight line (fig. 12*b*); these departures are commonly less than one unit in the third decimal place.[16] A dispersion formula built up on this relation is the two-constant formula of Cauchy, namely—

$$n = A + B/\lambda^2.$$

The formula may also be written

$$n - 1 = A' + B/\lambda^2.$$

[16] See Sellmeier, Ann. d. Phys. u. Chem., **143**, 272, 1871; also Pulfrich, Ann. d. Phys. u. Chem., **45**, 648, 1892; and Hovestadt, Jenaer Glas, p. 46–48. Jena, 1900.

In view of the fact that the range of refractive indices in optical glasses over the visible spectrum is relatively limited, any approximately straight-line relation between refractive index and a function of the wave length, such as expressed by the foregoing Cauchy formula, becomes an hyperbola if the reciprocal be taken of the refractive index or of the excess refractivity; but the portion of the curve covered by the visible spectrum is so short that, even in this case, the departure of the hyperbola from a straight line is not great and the dispersion relations are still fairly well represented. Thus, the new formula recently suggested by Nutting [17] is the Cauchy formula, in which $1/(n-1)$ is written for $(n-1)$. Nutting's formula represents the dispersions in certain cases better than the Cauchy formula, whereas in other glasses the Cauchy formula is the better. It would lead too far to present data of computation on a series of Gifford glasses which bear out this statement. The conclusion is, however, directly evident from a comparison of figures 18*a* and 18*b*, in which for all silicate glasses of Schott the squares of the frequency $(1/\lambda^2)$ are plotted as abscissæ against $\frac{n-1}{n_{A'}-1}$ and its reciprocal $\frac{n_{A'}-1}{n-1}$, respectively, as ordinates. As a result of this method of plotting all dispersion curves pass through the unit ordinate for the A′-spectrum line. The dispersion curves radiate from this point as approximately straight lines, the departures from straight lines being greatest in the dense flints and also in the very light crowns and borosilicate crowns.[18]

Another method of expressing these relations is to plot the frequency scale on the horizontal line at unit distance from the abscissa axis, to draw lines radiating from the origin through the points on the frequency scale, and to find the intercepts of these lines with ordinates equal to the refractive indices.[19] The dispersion curves under these conditions are approximately straight lines.

These relations suffice to prove that in any dispersion formula (if carried only over the visible spectrum in a transparent colorless substance, such as optical glass) which expresses the dispersion relations in approximately linear form, the reciprocals may be taken of the refractive index or any function of the same and the new dispersion curve thus obtained will again be approximately a straight line. In the ultra-violet and infra-red these relations may no longer obtain, and they inevitably break down as an absorption band is approached.

In figure 18*a* the effective refractivity $(n-1)$ for any wave length is expressed for each glass in terms of its effective refractivity for

[17] Revisita d'Ottica e Meccanica di Precisione, I, 54–57, 1919.

[18] Compare F. E. Wright, Jour. Opt. Soc. America, IV, 195–204, 1920.

[19] For a brief account of this method of plotting reciprocals see F. E. Wright, Jour. Wash. Acad. Sci., 10, 185–188, 1920.

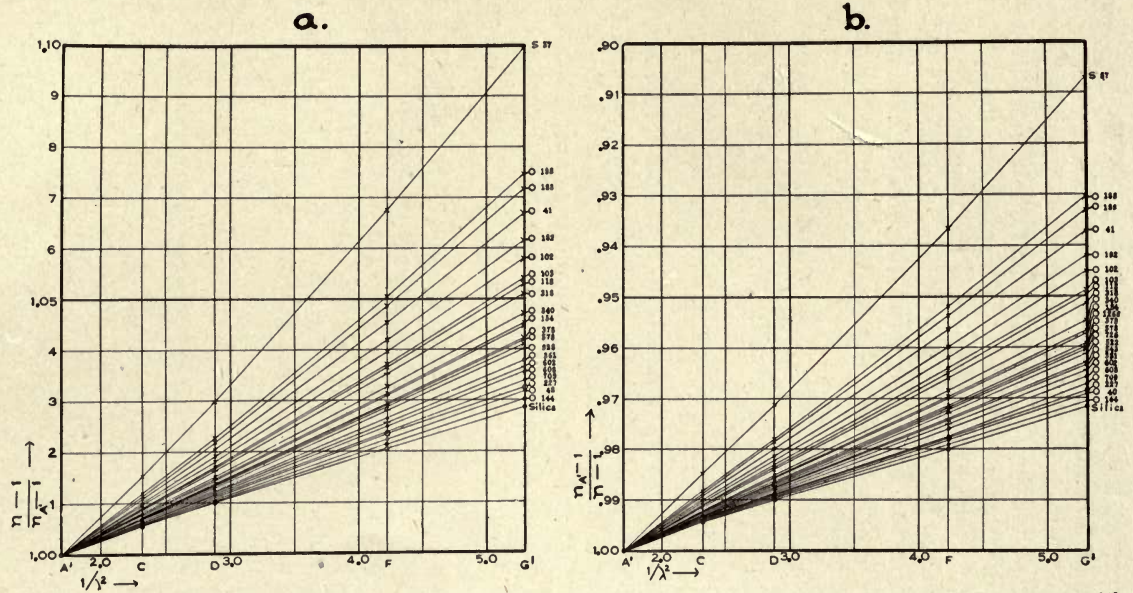

FIG. 18.—(*a*) In this figure the ratios $(n_r-1)/(n_A'-1)$ for a series of Schott glasses are plotted as ordinates against the squares of the frequency $(1/\lambda^2)$ as abscissæ. (*b*) The reciprocal ratios $(n_A'-1)/(n_r-1)$ are plotted as ordinates against the same abscissæ scale $(1/\lambda^2)$. The series of glasses represented in these figures are the same as those listed in Table 1 and include all types of silicates glases. These figures demonstrate clearly the feasibility of substituting in the Cauchy dispersion formula $1/(n-1)$ and thus obtaining the Nutting formula.

the A' wave length $(n_A - 1)$. The curves of this figure demonstrate that with rise in refractive index the dispersion also rises, and that, in the flint series especially, the dispersion increases relatively faster than the refractive index. This fact of increased rate of rise of dispersion with increase in absolute refringence is also clearly shown by a comparison of the dispersion relations in the flint series of glasses after reduction for each glass of all its refractive indices in the ratio n/n_D or $n/n_{A'}$. This procedure reduces the refractive index of each glass for the D-line or A'-line to unity, and thus renders the relations directly comparable. On plotting the ratios n/n_D against λ or $1/\lambda^2$ we find that, in spite of the reduction of all glasses to a common datum level of absolute refringence $(n_D = 1)$, the higher the refringence in the flint glass series the greater the slope of the dispersion curve, thus proving the relatively greater dispersion of the heavy flint glasses.

The foregoing relations, together with other relations, such as are shown by graphical plots in which: (a) $\frac{n_{G'} - n_F}{n_F - n_D}$ is plotted against $\frac{n_D - n_{A'}}{n_F - n_D}$, (b) $\frac{n_r}{n_D}$, against the wave length, λ_r, directly, (c) n_r against λ_r, (d) n_r against ν_r, demonstrate that the actual shape of a dispersion curve in optical glasses can be changed only in a definite manner and that the departures from any one of the set of standard dispersion curves do not exceed two units in the fourth decimal place. The effort of the glassmaker is therefore necessarily directed toward the production of glasses of different refringences for the same general run of dispersions.

In the foregoing paragraphs the dispersion relations in optical glasses are presented on diagrams in some detail and from different viewpoints purposely, because they are of fundamental importance to the study of dispersion not only in optical glasses, but also in other colorless substances. They indicate clearly the limits which the glassmaker has attained in his efforts to produce different types of optical glass and demonstrate that the paths which he may follow are narrowly prescribed.

RELATIONS BETWEEN CHEMICAL COMPOSITION AND REFRACTIVITY.

The study of the refractivity relations in optical glasses, as illustrated in the foregoing diagrams, indicates that certain chemical oxides in combination with silica dominate certain fields. To determine these relations, chemical analyses are essential. Unfortunately, the available analyses are not all of equal value. Table 4 contains the best chemical analyses of optical glasses whose optical constants are given and are at present known to the writer.[20] Many of these "analyses" are synthetic compositions computed from the batch compositions; in the table the sum in each "analysis" of this type is either 100.0 or 99.9.

[20] See also list of analyses published by Williams and Rand, J. American Ceramic Soc., 2, 434–441, 1919.

TABLE 4.—*Synthetic and actual chemical analyses of optical glasses of different types.*

In this table and accompanying legend are listed the chemical composition, the refractive index n_D, the ν value, the density d, and the partial dispersions (P. D.) of the several glasses so far as these have been determined. The abbreviation Zsch. refers to the list of chemical analyses published by E. Zschimmer in Doelter's Handbuch der Mineralchemie, Vol. I, pp. 869–889. 1914. The abbreviation (W) refers to the list of glass analyses published first by Winkelmann in the Ann. d. Phys. u. Chem., **49**, 401, 1893; **51**, 697, 730, 1894; **61**, 105, 1897; and later reproduced in Hovestadt's book on Jenaer Glas, Jena, 1900.

ORDINARY CROWNS.

No.	SiO_2.	B_2O_3.	Al_2O_3.	As_2O_3.	PbO.	ZnO.	CaO.	BaO.	K_2O.	Na_2O.	Total.	n_D.	ν.	d.
1	74.6	.....	.....	0.3	.....	.....	5.0	.....	11.0	9.0	100.0	1.5055	60.2	2.5
2	72.26	0.03	0.08	.....	.....	.....	11.61	.....	0.20	13.81	98.50	1.5261	59.3	.....
3	71.34	.....	.09	.90	.....	.....	12.51	.....	.10	13.42	98.73	1.5250	59.1	.....
4	70.6	.....	.....	.3	.....	.....	11.0	.....	16.0	2.0	100.0	1.5179	60.2	2.49
5	71.6	.....	.....	.7	.....	.....	8.0	2.6	9.0	8.1	100.0	1.516	60.0	.....
6	69.3	.....	.3	.3	.....	.....	10.3	.....	19.2	0.2	99.6	1.5176	60.1	.....
BOROSILICATE CROWNS.														
7	72.15	5.88	0.01	0.08	.....	.....	2.04	.....	13.85	5.16	99.74	1.5102	64.1	2.47
8	70.4	7.5	.....	.2	.....	.....	2.0	.....	14.5	5.3	100.0	1.5100	64.0	2.47
9	70.0	8.0	.....	.2	.....	.....	2.0	.....	14.5	5.3	100.0	1.5118	63.5	2.47
10	70.0	8.3	.....	.3	.....	.....	1.9	.....	12.0	7.4	100.0	1.511	64.1	.....
11	68.2	10.0	.....	.2	.....	.....	2.0	.....	9.5	10.0	100.0	1.5116	63.5	2.47
12	72.0	12.0	5.0	.....	.....	.....	.....	.....	.....	11.0	100.0	1.4997	64.7	2.37
13	71.0	14.0	5.0	.....	.....	.....	.....	.....	.....	10.0	100.0	1.4990	64.6	2.37
14	71.23	8.20	1.47	.....	.....	.....	1.99	.....	12.58	3.63	99.48	1.5140	63.1	.....
15	70.6	6.0	1.0	.3	.....	.....	.....	.....	10.5	11.5	100.0	1.5069	62.3	2.48
16	70.95	6.30	.88	.20	.....	1.46	0.17	.....	9.22	10.11	99.51	1.5079	62.1	.....
17	69.58	9.91	.04	.09	.....	.....	.07	2.54	8.37	8.44	99.54	1.5164	64.0	.....
18	69.0	2.5	.....	.4	.....	.....	8.0	.....	16.0	4.0	100.0	1.5168	60.9	2.49
19	68.5	3.5	.....	.3	.....	1.0	.....	9.7	5.0	12.0	100.0	1.5183	60.4	2.63
20	68.1	3.5	.....	.4	.....	7.0	.....	.....	16.0	5.0	100.0	1.5107	60.5	2.5
21	67.73	9.98	.06	.....	.....	1.78	.05	.....	10.07	9.29	99.51	1.5142	64.0	.....
22	65.6	4.5	.....	.4	.....	11.5	.....	.....	3.5	14.5	100.0	1.5175	60.2	2.59
23	65.5	2.5	.....	.4	.....	2.0	.....	9.6	15.0	5.0	100.0	1.5173	60.4	2.49
24	64.6	2.7	.....	.4	.....	2.0	.....	10.2	15.0	5.0	100.0	1.5179	60.2	2.58
25	53.5	20.0	.....	.....	.....	.....	.....	.....	6.5	.....	100.0	1.5159	53.6	2.6
ZINC SILICATE CROWN.														
26	71.0	.....	.....	.....	.....	12.0	.....	.....	.....	17.0	100.0	1.5128	57.3	2.57

TABLE 4.—*Synthetic and actual chemical analyses of optical glasses of different types*—Continued.

BARIUM CROWNS.

No.	SiO_2.	B_2O_3.	Al_2O_3.	As_2O_3.	PbO.	ZnO.	CaO.	BaO.	K_2O.	Na_2O.	Total.	n_D.	ν.	d.
27	59.5	3.0	.....	0.3	.....	5.0	.....	19.2	10.0	3.0	100.0	1.5408	59.8	2.73
28	59.13	3.04	0.11	.34	.....	5.00	0.13	19.25	9.70	3.16	99.88	1.5409	59.6	.....
29	48.8	3.0	.....	.4	.....	10.3	.....	29.0	7.5	1.0	100.0	1.5727	58.0	.....
30	48.9	3.8	1.0	.3	.....	8.9	.....	28.6	4.3	4.3	100.0	1.570	57.0	.....
31	48.2	3.7	1.0	.3	.....	8.8	.....	29.5	7.5	1.0	100.0	1.5724	57.6	3.21
32	48.1	4.5	.....	.4	.....	10.1	.....	28.3	7.5	1.0	100.0	1.5726	57.5	3.21
33	47.8	4.5	.....	.3	.....	10.3	.....	28.5	7.5	1.0	100.0	1.5742	57.2	3.21
34	47.73	3.90	.65	.38	.....	8.61	.15	29.88	7.16	1.14	99.84	1.5726	57.4	.....
35	46.9	4.5	.....	.5	.....	10.5	.....	29.0	7.5	1.0	99.9	1.5748	56.9	3.21
36	48.8	3.0	.....	.3	4.1	15.5	.....	21.0	6.5	.8	100.0	1.5791	53.6	3.26
37	45.02	4.50	.09	.06	4.70	15.53	.....	22.39	6.80	.64	100.18	1.5795	53.8	.....
38	39.6	6.0	2.5	.5	.....	9.2	.....	42.1	.....	.....	100.0	1.6090	56.6	3.55
39	40.17	5.96	2.79	.03	.....	8.17	.03	42.35	.03	.13	100.17	1.6095	56.8	.....
40	37.5	15.0	5.0	1.5	.....	.....	.....	41.0	.....	.....	100.0	1.5899	60.8	3.32
41	38.66	13.36	5.11	.37	.....	.....	.....	41.53	.05	.30	99.38	1.5904	61.3	.....
42	37.3	6.0	2.0	.....	.....	10.8	.....	40.5	.....	3.2	99.8	1.6097	55.7	.....
43	34.5	10.1	5.0	.5	.....	7.8	.....	42.0	.....	.....	100.0	1.6088	57.0	3.53
44	34.56	10.96	5.02	.04	.....	1.14	.....	46.91	.09	.21	99.48	1.6091	58.8	.....
45	31.0	12.0	8.0	1.0	.....	.....	.....	48.0	.....	.....	100.0	1.6098	58.8	3.54

FLINTS.

46	69.2	.....	.....	0.3	6.5	.....	4.0	.....	17.0	3.0	100.0	1.5151	56.6	2.55
47	68.7	.....	.....	.2	13.3	2.0	.....	.....	.....	15.7	100.0	1.5202	51.6	2.7
48	68.2	.....	.....	.2	13.1	2.0	.....	.....	.....	16.5	100.0	1.5219	51.5	2.7
49	67.40	.....	1.72	.14	10.71	3.85	.39	.....	.14	15.13	99.69	1.5221	52.2	.....
50	66.8	.....	1.5	.2	11.6	3.8	.....	.....	.....	16.0	100.0	1.5228	52.0	2.7
51	65.9	.....	2.0	.2	16.3	.....	.....	.....	.....	15.5	99.9	1.5230	50.8	2.70
52	62.6	.....	.....	.3	24.1	.....	.....	.....	8.5	4.5	100.0	1.5414	46.9	2.87
53	59.3	.....	.....	.26	27.5	.....	.....	.....	8.0	5.0	100.0	1.5537	45.0	2.9
54	54.75	0.45	.04	.0	29.3	.96	.05	1.64	7.99	4.31	99.97	1.5711	43.0	.....
55	54.3	1.5	.....	.2	33.0	.....	.....	.....	8.0	3.0	100.0	1.5710	43.0	.....
56	53.7	.....	.....	.3	36.6	.....	.....	.....	8.3	1.0	100.0	1.5752	41.0	3.22
57	52.53	.30	.01	.13	34.42	.03	.04	.....	8.21	3.78	99.72	1.5802	41.0	.....
58	52.7	.....	.....	.4	35.0	.....	.....	.....	5.5	6.3	100.0	1.580	41.1	.....
59	48.7	.....	.....	.3	42.0	.....	.....	.....	5.0	4.0	100.0	1.6054	37.9	3.5
60	47.9	.....	.....	.3	42.4	.....	.....	.....	5.1	4.3	100.0	1.605	37.6	.....
61	46.6	.....	.....	.3	43.8	.....	.....	.....	7.8	1.5	100.0	1.6137	36.9	3.58
62	46.12	.....	.06	.35	45.13	.....	.07	.....	6.78	1.72	100.38	1.6163	36.6	.....
63	46.32	.....	.02	.....	45.03	.....	.25	.....	5.63	2.48	99.82	1.6162	36.6	.....
64	45.40	.....	.....	.3	45.1	.....	.....	.....	7.7	1.5	100.0	1.6243	35.9	3.68

65	45.2			.2	46.0				7.5	1.0	100.6	1.6153	36.7	3.58
66	44.1				44.7				9.8	1.2	99.8	1.6188	36.2	3.6
67	47.6			.2	46.7				5.0	.5	100.0	1.6129	36.9	3.58
68	45.64		.03	.22	43.45		.05		8.66	1.77	99.82	1.6137	36.9	
69	45.2		.5	.2	46.4				7.5	.2	100.0	1.6123	37.0	3.58
70	43.9			.2	47.3				8.0	.5	100.0	1.6130	37.0	3.58
71	44.6			.3	46.6				8.0	.5	100.0	1.6207	36.1	3.63
72	41.7			.3	50.5				7.0	.5	100.0	1.6485	33.8	3.87
73	41.7			.3	50.5				4.0	3.5	100.0	1.6400	34.6	
74	41.0			.2	51.7				7.0		100.0	1.6450	34.1	3.88
75	40.99		.04	.22	51.13		.13		6.93	.61	100.15	1.6485	33.8	
76	40.0			.3	52.6				6.5	.5	100.0	1.6500	33.6	3.87
77	39.2			.3	51.0			2.0	5.0	2.5	100.0	1.6657	32.9	4.1
78	38.0			.2	56.8				5.0		100.0	1.6801	31.7	4.1
79	34.7			.3	61.0				2.5	1.5	100.0	1.7172	29.5	4.49
80	33.7			.3	62.0				4.0		100.0	1.7174	29.5	4.49
81	29.3			.2	67.5				3.0		100.0	1.7510	27.6	4.73
82	28.4			.1	69.0				2.5		100.0	1.7541	27.5	4.78
83	27.3			.1	71.0				1.5		99.9	1.7782	26.5	4.99
84	22.0				78.0						100.0	1.8904	22.3	5.83
85	21.0				79.0						100.0	1.9068	21.6	
86	20.0				80.0						100.0	1.9053	21.7	5.94
87	18.0			.1	82.0						100.1	1.9626	19.7	6.33

BOROSILICATE FLINT.

88	29.0	29.0	10.0		30.0				0.5	1.5	100.0	1.5676	46.7	2.97

BARIUM FLINT.

No.	SiO_2	B_2O_3	Al_2O_3	As_2O_3	PbO	ZnO	CaO	BaO	K_2O	Na_2O	Total.	n_D	V	d
89	56.2			0.3	7.0	9.0		15.0	11.0	1.5	100.0	1.5500	53.3	3.0
90	55.9			.3	17.3			11.5	13.0	2.0	100.0	1.5560	48.6	3.03
91	53.5			.3	11.0	10.0		14.2	9.5	1.5	100.0	1.5630	50.8	3.11
92	51.6			.3	11.0	12.0		14.0	9.5	1.5	99.9	1.5637	50.6	3.11
93	51.7			.3	10.0	7.0		20.0	9.5	1.5	100.0	1.5718	50.4	3.19
94	50.2			.4	10.3	10.6		17.7	9.5	1.3	100.0	1.5745	50.2	3.2
95	51.2			.3	4.0	14.0		20.0	5.0	5.5	100.0	1.5692	52.9	3.12
96	50.2			.5	18.5	8.2		13.1	8.5	1.0	100.0	1.5832	46.3	3.29
97	49.80		0.05	.01	18.74	8.03		13.35	8.20	1.24	100.03	1.5832	46.3	
98	49.1			.5	19.3	8.5		13.0	8.5	1.0	100.0	1.5822	46.3	3.29
99	45.2			.4	22.2	8.3		16.0	7.8		100.0	1.6042	43.9	3.50
100	45.2			.4	22.8	8.2		15.5	7.3	.5	100.0	1.6026	44.2	3.40
101	43.8			.3	38.1	3.1		6.5	8.3		100.0	1.619	37.6	
102	42.8			.5	32.6	5.1		10.8	7.5	.7	100.0	1.6269	39.1	3.70

TABLE 4.—*Synthetic and actual chemical analyses of optical glasses of different types*—Continued.

BORATE GLASSES.

No.	B_2O_3	P_2O_5	Al_2O_3	As_2O_3	PbO	ZnO	BaO	K_2O	Na_2O	Total	n_D	V	d
103	69.1	.....	18.0	0.2	.....	.....	4.7	.....	8.0	100.0	1.5085	60.4	2.24
104	63.8	.....	18.0	.2	3.0	.....	3.5	3.5	8.0	100.0	1.5101	58.9	2.2
105	56.0	.....	12.0	.....	32.0	.....	.....	.....	.....	100.0	1.5734	46.9	3.0
106	49.7	.....	13.0	.3	37.0	.....	.....	.....	.....	100.0	1.6130	44.4	3.17
107	46.5	.....	7.5	.2	46.0	.....	.....	.....	.....	100.0	1.6287	42.5	.....
108	42.8	.....	5.0	.2	52.0	.....	.....	.....	.....	100.0	1.6659	39.2	3.69
109	41.0	.....	.....	.....	.....	59.0	.....	.....	.....	100.0	1.6525	50.8	3.53
110	71.8	.....	22.4	.....	.....	.....	.....	.....	.....	100.0	1.5232	61.4	2.24
111	64.0	.....	30.0	.....	.....	.....	.....	.....	.....	100.0	1.5194	60.9	2.21

PHOSPHATE GLASSES.

112	3.0	70.5	10.0	0.5	.....	.....	.....	12.0	.....	100.0	1.5159	70.0	2.59
113	3.0	69.5	10.0	1.5	.....	.....	.....	12.0	.....	100.0	1.5215	69.7	2.59
114	3.0	59.5	8.0	1.5	.....	.....	28.0	.....	.....	100.0	1.5583	67.0	3.07
115	3.0	56.0	1.5	1.5	.....	.....	38.0	.....	.....	100.0	1.5670	65.6	3.24
116	3.0	54.0	1.5	1.5	.....	.....	40.0	.....	.....	100.0	1.5760	65.2	3.35
117	3.0	45.0	.....	2.0	.....	.....	50.0	.....	.....	100.0	1.5906	64.1	3.66

ORDINARY CROWNS.

1. Ordinary crown.—Zsch. 69 (W 91). With Mn_2O_3, 0.1.
2. Crown plate-glass.—Freden, Germany. E. T. Allen, analyst. With $Al_2O_3+Fe_2O_3$, 0.08; Sb_2O_3, 0.51.
3. Crown plate-glass.—Pittsburgh Plate Glass Co. E. T. Allen, analyst. With $Al_2O_3+Fe_2O_3$, 0.09.
4. Ordinary crown.—Zsch. 80. With Mn_2O_3, 0.1.
5. Light crown.—Spencer Lens Co. C. N. Fenner, J. Am. Ceram. Soc., II, 143, 1919.
6. Hard crown.—Chance Bros. Zsch. 31. With $Al_2O_3+Fe_2O_3$, 0.3. P. D.: F-D=0.00856; F-D=0.00604; G'-F=0.00484.

BOROSILICATE CROWNS.

7. Borosilicate crown.—Schott O 144. E. T. Allen, analyst. J. Am. Ceram. Soc., I, 784, 1918. With Fe_2O_3, 0.1; As_2O_5, 0.20; H_2O, 0.08; SO_3, 0.12; Cl, 0.05.
8. Borosilicate crown.—Schott O 144. Zsch. 137 (W 88). With Mn_2O_3, 0.1. P. D.: F-C=0.00797; D-A'=0.00519; F-D=0.00559; G'-F=0.00446.
9. Borosilicate crown.—Schott O 144 (O 1948). Zsch. 138.
10. Borosilicate crown.—Spencer Lens Co. C. N. Fenner, J. Am. Ceram. Soc., II, 143, 1919.
11. Borosilicate crown.—Schott O 144 (O 627). Zsch. 141 (W 49, 87). With Mn_2O_3, 0.1.
12. Borosilicate crown.—Schott G 59 III. Zsch. 152. Thermometer glass.
13. Borosilicate crown.—Schott O 802 (O 1450). Zsch. 153 (W 5). P. D.: F-C=0.00765; D-A'=0.00504; F-D=0.00534; G'-F=0.00423.
14. Borosilicate crown.—National Opt. Co. E. T. Allen, analyst. With Fe_2O_3, 0.04; PbO, 0.12; MgO, 0.09; H_2O, 0.06; SO_3, 0.02; Cl, 0.05.
15. Borosilicate crown.—Schott O 599. Zsch. 134. With Mn_2O_3, 0.1. P. D.: F-C=0.00813; D-A'=0.00529; F-D=0.00569; G'-F=0.00457.
16. Borosilicate crown.—Schott O 599. E. T. Allen, analyst. With $Al_2O_3+Fe_2O_3$, 0.88; H_2O, 0.16; SO_3, 0.06.

17. Borosilicate crown.—Schott O 3832. E. T. Allen, analyst. J. Am. Ceram. Soc., I, 784, 1918. With Fe_2O_3, 0.01; As_2O_5, 0.22; MgO, 0.07; H_2O, 0.06; SO_3, 0.08; Cl, 0.06. P. D.: F–C=0.00806; D–A'=0.00528; F–D=0.00566; G'–F=0.00448.
18. Borosilicate crown.—Schott O 40 (O 55). Zsch. 136 (W 52, 89). With Mn_2O_3, 0.1. P. D.: F–C=0.00849; D–A'=0.00545; F–D=0.00596; G'–F=0.00479.
19. Borosilicate crown.—Schott O 453 (O 4418). Zsch. 146. P. D.: F–C=0.00860; D–A'=0.00550; F–D=0.00605; G'–F=0.00486.
20. Borosilicate crown.—Schott O 374 (O 662). Zsch. 139 (W 56). P. D.: F–C=0.00844; D–A'=0.00547; F–D=0.00593; G'–F=0.00479.
21. Borosilicate crown.—National Opt. Co. E. T. Allen, analyst. With Fe_2O_3, 0.05; Mn_2O_3, 0.03; MgO, 0.17; H_2O, 0.10; SO_3, 0.20.
22. Borosilicate crown.—Schott O 546 (O 518). Zsch. 140. P. D.: F–C=0.00859; D–A'=0.00555; F–D=0.00605; G'–F=0.00485.
23. Borosilicate crown.—Schott O 60 (O 122, O 1092). Zsch. 142 (W 60, 77). P. D.: F–C=0.00853; D–A'=0.00555; F–D=0.00601; G'–F=0.00489.
24. Borosilicate crown.—Schott O 60. Zsch. 143 (W 28). P. D.: F–C=0.00860; D–A'=0.00553; F–D=0.00605; G'–F=0.00487.
25. Borosilicate crown.—Schott O 608. Zsch. 131 with Sb_2O_3 20.0. P. D.: F–C=0.00943; D–A'=0.00595; F–D=0.00666; G'–F=0.00543.

ZINC SILICATE CROWN.

26. Zinc silicate crown.—Schott O 709. Zsch. 16 (W 25, 79). P. D.: F–C=0.00894; D–A'=0.00575; F–D=0.00630; G'–F=0.00508.

BARIUM CROWNS.

27. Barium crown.—Schott O 227 (O 3855). Zsch. 145. P. D.; F–C=0.00909; D–A'=0.00582; F–D=0.00639; G'–F=0.00514.
28. Barium crown.—Schott O 227. E. Zies, analyst. J. Am. Ceram. Soc., I, 784, 1918. With Fe_2O_3, 0.02.
29. Barium crown.—Schott O 211 (O 885). Zsch. 144 (W. 48).
30. Barium crown.—Spencer Lens Co. C. N. Fenner, J. Am. Ceram. Soc., II, 143, 1919.
31. Barium crown.—Schott O 211 (O 4556). Zsch. 147.
32. Barium crown.—Schott O 211. Zsch. 150 (W. 85). With Mn_2O_3, 0.1. P. D. F–C=0.00995; D–A'=0.00630; F–D=0.00702; G'–F=0.00588.
33. Barium crown.—Schott O 211 (O 1143). Zsch. 149. With Mn_2O_3, 0.1. P. D.: F–C=0.01006; D–A'=0.00640; F–D=0.00704; G'–F=0.00584.
34. Barium crown.—Schott O 211. E. T. Allen; analyst. With Fe_2O_3, 0.01; MgO, 0.02; H_2O, 0.14, SO_3, 0.04; Cl, 0.03.
35. Barium crown.—Schott O 211 (O 1580). Zsch. 148.
36. Barium crown.—Schott O 722. Zsch. 133.
37. Barium crown.—Schott O 722. E. Zies, analyst. J. Am. Ceram. Soc. I, 784, 1918. With Al_2O_3+Fe_2O_3=0.09; As_2O_5=0.55. P. D.: F–C=0.01078; D–A'=0.00681; F–D=0.00761; G'–F=0.00621.
38. Barium crown.—Schott O 1209 (O 1922). Zsch. 151. With Mn_2O_3, 0.1.
39. Barium crown.—Schott O 1209. E. T. Allen, analyst. J. Am. Ceram. Soc., I, 784, 1918. With Fe_2O_3, 0.02; As_2O_5, 0.49. P. D.: F–C=0.01068; D–A'=0.00680; F–D=0.00753; G'–F=0.00610.
40. Barium crown.—Schott O 2122. Zsch. 161. P. D.: F–C=0.00970; D–A'=0.00621; F–D=0.00683; G'–F=0.00546.
41. Barium crown.—Schott O 2122. E. T. Allen, analyst. J. Am. Ceram. Soc., I, 784, 1918. With Al_2O_3+Fe_2O_3=5.11.
42. Barium crown.—Mantois. Zsch. 127.
43. Barium crown.—Schott O 1029 (O 1299). Zsch. 162 (W. 15, 23). With Mn_2O_3, 0.1. P. D.: F–C=0.01068; D–A'=0.00680; F–D=0.00753; G'–F=0.00610.
44. Barium crown.—Schott O 2071. E. T. Allen, analyst. J. Am. Ceram. Soc., I, 784, 1918. With Al_2O_3, 5.02; As_2O_5, 0.55.
45. Barium crown.—Schott, O 2071. Zsch. 160. P. D.: F–C=0.01037; D–A'=0.00665; F–D=0.00730; G'–F=0.00590.

FLINTS.

46. Crown of high dispersion.—Schott O 114. Zsch. 98. P. D.: F–C=0.00910; D–A'=0.00577; F–D=0.00642; G'–F=0.00521.
47. Flint.—Schott O 381 (O 1151). Zsch. 30. With Mn_2O_3, 0.1. P. D.: F–C=0.01026; D–A'=0.00644; F–D=0.00727; G'–F=0.00596.
48. Flint.—Schott O 381 (O 1168). Zsch. 29 (W 55).
49. Flint.—Schott O 381. E. Posnjak, analyst. With Fe_2O_3, 0.02; Mn_2O_3, 0.04; H_2O, 0.15.
50. Flint.—Schott O 381 (O 2074). Zsch. 27. With Mn_2O_3, 0.1.
51. Flint.—Schott O 381 (O 1335). Zsch. 20.
52. Flint.—Schott O 726 (O 3149). Zsch. 86. P. D.: F–C=0.01142; D–A'=0.00711; F–D=0.00810; G'–F=0.00669.
53. Flint.—Schott O 378 (O 3807). Zsch. 88. P. D.: F–C=0.01193; D–A'=0.00739; F–D=0.00847; G'–F=0.00705.
54. Flint.—Schott O 154. E. T. Allen, analyst. J. Am. Ceram. Soc., I, 784, 1918. With Fe_2O_3, 0.02; As_2O_5, 0.14; H_2O, 0.20; Cl. 0.06. P. D.: F–C=0.01327; D–A'=0.00819; F–D=0.00943; G'–F=0.00791.
55. Flint.—Schott O 154. Zsch. 89 (W 47). With Mn_2O_3, 0.1.
56. Flint.—Schott O 569 (O 451). Zsch. 90. With Mn_2O_3, 0.1. P. D.: F–C=0.01385; D–A'=0.00853; F–D=0.00987; G'–F=0.00831.
57. Flint.—Schott O 340. E. T. Allen, analyst. With Fe_2O_3, 0.02; H_2O, 0.09; SO_3, 0.10; Cl, 0.03. P. D.: F–C=0.01396; D–A'=0.00857; F–D=0.00994; G'–F=0.00837.

58. Flint.—Spencer Lens Co. C. N. Fenner, J. Am. Ceram. Soc., II, 143, 1919.
59. Flint.—Schott 318 (O 4369). Zsch. 91. P. D.: $F-C=0.01575$; $D-A'=0.00960$; $F-D=0.01124$; $G'-F=0.00952$.
60. Flint.—Spencer Lens Co. C. N. Fenner, J. Am. Ceram. Soc. II, 143, 1919.
61. Flint.—Schott O 118 (O 4271). Zsch. 92. P. D.: $F-C=0.01660$; $D-A'=0.01006$; $F-D=0.01184$; $G'-F=0.01008$.
62. Flint.—Schott O 167. E. Zies, analyst. J. Am. Ceram. Soc., I, 784, 1918. With Fe_2O_3, 0.02; H_2O, 0.03; SO_3, 0.10.
63. Flint.—National Opt. Co. E. T. Allen, analyst. J. Am. Ceram. Soc., I, 784, 1918. With Fe_2O_3, 0.03; H_2O, 0.06.
64. Flint.—Schott O 93 (O 4237). Zsch. 94. P. D.: $F-C=0.01743$; $D-A'=0.01053$; $F-D=0.01243$; $G'-F=0.01063$.
65. Flint.—Schott O 331. Zsch. 95. With Mn_2O_3, 0.1.
66. Flint.—Mantois. Zsch. 93.
67. Flint.—Schott O 118. Zsch. 50. P. D.: $F-C=0.01660$; $D-A'=0.01006$; $F-D=0.01184$; $G'-F=0.01008$.
68. Flint.—Schott O 118. E. T. Allen, analyst. With $Al_2O_3+Fe_2O_3=0.03$.
69. Flint.—Schott O 118 (O 479). Zsch. 47 (W 46).
70. Flint.—Schott O 118 (O 1469). Zsch. 52. With Mn_2O_3, 0.1.
71. Flint.—Schott O 103 (O 2512). Zsch. 49. P. D.: $F-C=0.01709$; $D-A'=0.01034$; $F-D=0.01220$; $G'-F=0.01041$.
72. Flint.—Schott O 102 (O 4591). Zsch. 53. P. D.: $F-C=0.01919$; $D-A'=0.01152$; $F-D=0.01372$; $G'-F=0.01180$.
73. Flint.—Spencer Lens Co. C. N. Fenner. J. Am. Ceram. Soc., II, 143, 1919.
74. Flint.—Schott O 102 (O 1571). Zsch. 54 (W 25). With Mn_2O_3, 0.1.
75. Flint.—Schott O 102. E. Posnjak, analyst. With Fe_2O_3, 0.02; H_2O, 0.08.
76. Flint.—Schott O 102 (O 469). Zsch. 55. With Mn_2O_3, 0.1. P. D.: $F-C=0.01927$; $D-A'=0.01161$; $F-D=0.01382$; $G'-F=0.01194$.
77. Flint.—Schott O 192 (O 3570). Zsch. 101.
78. Flint.—Schott O 192. Zsch. 57. P. D.: $F-C=0.02104$; $D-A'=0.01255$; $F-D=0.01507$; $G'-F=0.01302$.
79. Flint.—Schott O 41 (O 4113). Zsch. 96.
80. Flint.—Schott O 41. Zsch. 58. P. D.: $F-C=0.02434$; $D-A'=0.01439$; $F-D=0.01749$; $G'-F=0.01521$.
81. Flint.—Schott O 165 (O 500). Zsch. 59 (W 33). P. D.: $F-C=0.02723$; $D-A'=0.01600$; $F-D=0.01961$; $G'-F=0.01709$.
82. Flint.—Schott O 165. Zsch. 60 (W 50). P. D.: $F-C=0.02743$; $D-A'=0.01607$; $F-D=0.01974$; $G'-F=0.01730$.
83. Flint.—Schott O 198. Zsch. 61. P. D.: $F-C=0.02941$; $D-A'=0.01719$; $F-D=0.02120$; $G'-F=0.01868$.
84. Flint.—Schott S 163. Zsch. 110 (W 18). P. D.: $F-C=0.03997$; $D-A'=0.02293$; $F-D=0.02895$; $G'-F=0.02603$.
85. Flint.—Schott S 231. Zsch. 111 (W 64).
86. Flint.—Schott S 208. Zsch. 112 (W 20).
87. Flint.—Schott S 57. Zsch. 113. P. D.: $F-C=0.04882$; $D-A'=0.02767$; $F-D=0.03547$; $G'-F=0.03252$.

BOROSILICATE FLINT.

88. Borosilicate flint.—Schott O 161. Zsch. 157. P. D.: $F-C=0.01216$; $D-A'=0.00732$; $F-D=0.00860$; $G'-F=0.00709$.

BARIUM FLINT.

89. Barium flint.—Schott O 846 (O 3666). Zsch. 103. P. D.: $F-C=0.01042$; $D-A'=0.00657$; $F-D=0.00736$; $G'-F=0.00602$.
90. Barium flint.—Schott O 522 (O 3533). Zsch. 100. P. D.: $F-C=0.01153$; $D-A'=0.00718$; $F-D=0.00819$; $G'-F=0.00677$.
91. Barium flint.—Schott O 543 (O 3868). Zsch. 106.
92. Barium flint.—Schott O 543. Zsch. 107. P. D.: $F-C=0.01115$; $D-A'=0.00699$; $F-D=0.00790$; $G'-F=0.00650$.
93. Barium flint.—Schott O 527. Zsch. 104. P. D.: $F-C=0.01133$; $D-A'=0.00706$; $F-D=0.00803$; $G'-F=0.00660$.
94. Barium flint.—Schott O 527 (O 3187). Zsch. 105.
95. Barium flint.—Schott O 602 (O 3524). Zsch. 102. P. D.: $F-C=0.01072$; $D-A'=0.00675$; $F-D=0.00759$; $G'-F=0.00618$.
96. Barium flint.—Schott O 578 (O 4542). Zsch. 108.
97. Barium flint.—Schott O 578. E. Posnjak, Analyst. J. Am. Ceram. Soc., I, 784, 1918. With Fe_2O_3, 0.01; As_2O_5, 0.51; H_2O, 0.08. P. D.: $F-C=0.01255$; $D-A'=0.00777$; $F-D=0.00891$; $G'-F=0.00739$.
98. Barium flint.—Schott O 578 (O 1398). Zsch. 109. With Mn_2O_3, 0.1. P. D.: $F-C=0.01244$; $D-A'=0.00774$; $F-D=0.00896$; $G'-F=0.00742$.
99. Barium flint.—Schott O 1266 (O 3111). Zsch. 64. With Mn_2O_3, 0.1. P. D.: $F-C=0.01381$; $D-A'=0.00851$; $F-D=0.00982$; $G'-F=0.00821$.
100. Barium flint.—Schott O 1266 (O 1777). Zsch. 65. With Mn_2O_3, 0.1.
101. Barium flint.—Spencer Lens Co. C. N. Fenner. J. Am. Ceram. Soc., II, 146, 1919.
102. Barium flint.—Schott O 748 (O 4534). Zsch. 66. P. D.: $F-C=0.01599$; $D-A'=0.00965$; $F-D=0.01142$; $G'-F=0.00965$.

BORATE GLASS.

103. Borate glass.—Schott S 196. Zsch. 171 (W 2).
104. Borate glass.—Schott S 204. Zsch. 173.
105. Borate glass.—Schott V S 428. Zsch. 167 (W 42).
106. Borate glass.—Schott S 4. Zsch. 168.
107. Borate glass.—Schott S 99. Zsch. 169.
108. Borate glass.—Schott S 120. Zsch. 170 (W 16).
109. Borate glass.—Schott V S 665. Zsch. 164.
110. Borate glass.—Schott S 185. Zsch. 165 (W 1). With Li_2O, 5.8.
111. Borate glass.—Schott V S 458. Zsch. 166 (W 43). With Li_2O, 6.0.

PHOSPHATE GLASS.

112. Phosphate glass.—Schott O 225. Zsch. 179 (W 9, 57). With MgO, 4.0. P. D.: $F-C=0.00737$; $D-A'=0.00485$; $F-D=0.00517$; $G'-F=0.00407$.
113. Phosphate glass.—Schott S 219. Zsch. 178 (W 27). With MgO, 4.0.
114. Phosphate glass.—Schott S. 206. Zsch. 177 (W 13).
115. Phosphate glass.—Schott S 95. Zsch. 174 (W 14).
116. Phosphate glass.—Schott S 30. Zsch. 175. P. D.: $F-C=0.00884$; $D-A'=0.00570$; $F-D=0.00622$; $G'-F=0.00500$.
117. Phosphate glass.—Schott S 15. Zsch. 176. P. D.: $F-C=0.00922$; $D-A'=0.00591$; $F-D=0.00648$; $G'-F=0.00521$.

Table 4 includes 16 precision analyses of a number of types of foreign optical glass; these analyses were made with the greatest care by Drs. E. T. Allen, E. Zies, and E. Posnjak, of the Geophysical Laboratory, and are interesting not only because they furnish reliable data on the essential components of the glasses, but because they prove that the German glasses contain almost negligible amounts of impurities; in short, that the excellence of these glasses is the result of the use of raw materials of high chemical purity and of crucibles of resistant qualities. The analysis of optical glasses is not an easy task and special methods for such work were developed and perfected by Allen and Zies.[21] Table 4 contains also a number of selected analyses (largely synthetic and deduced evidently from the batch compositions) from a list published by E. Zschimmer in C. Doelter's Handbuch der Mineralchemie, I, pages 869–888, 1912. Many of the analyses in the Zschimmer list were published first by Winkelmann and others and are given in the book on Jena glass by H. Hovestadt (translation by J. D. and A. Everett, London, 1902) on pages 146–147. The Winkelmann-Hovestadt numbers are included in Table 4. A number of these synthetic analyses have been checked by chemical analyses of the glasses; the results have been in general in fair accord. Analyses computed from the batches of certain other glasses are also included. In Table 4 the refractive index n_D, the ν-value, and the density of each glass are listed; also the dispersions of the standard type glasses cited in the optical glass lists of Schott and of Chance. In each case these dispersions are sufficiently near the actual dispersions of the glass whose analysis is given to be substituted for them.

The simplest series of optical glasses is evidently the flint series, and for this reason this series was studied first and certain composition-refractivity relations were deduced from it. The chemical relations (weight percentages) were plotted on a triaxial diagram, such as is commonly used in representing the relations in a three-component chemical system.

The fact that, for the members of the flint series, the refractivity relations are expressed by means of smooth continuous curves in the foregoing diagrams 13, 14, and 15, indicates that this series is analogous in its behavior, so far as the flint glasses are concerned, to a two-component system. If so, the chemical composition of these glasses, when plotted in the triaxial diagram, should be found to fall on a straight line. In figure 19 the weight-percentage compositions are plotted directly; the three components are silica (SiO_2), lead oxide (PbO), and the alkali oxides (Na_2O, K_2O). The points on the diagram include all available compositions of flint glasses. The potash flints are distinguished in the diagram from the soda-

[21] Jour. Am. Ceram Soc., I, 739–786, 1918.

potash flints and from the soda flints. The compositions of all the glasses plotted fall on a practically straight line between the compositions: Lead metasilicate ($PbO.SiO_2$) and the potassium silicate glass of the composition ($K_2O.6SiO_2$), or the sodium silicate glass of the approximate composition $Na_2O.4SiO_2$. The optical constants of a synthetic potassium silicate glass of this composition were found to be $n_D = 1.4836$, $\nu = 61.0$.

The entire flint series is analogous chemically to a two-component mixture; and, as such, any one of its physical constants such as refractive index, ν-value, or density varies continuously with change

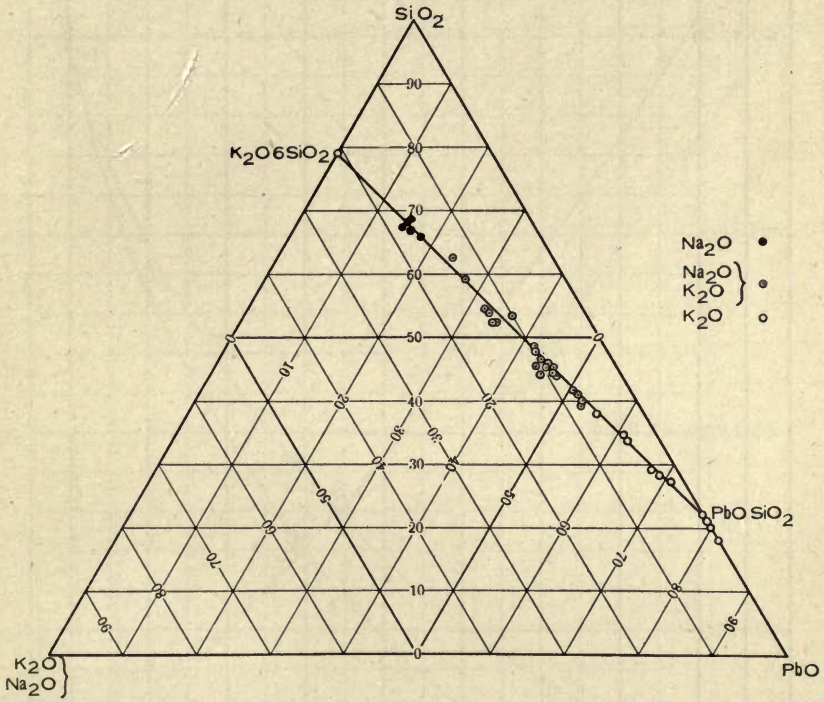

FIG. 19.—Triaxial diagram showing the weight-percentage compositions of the potash flint, soda-potash flint, and soda-flint glasses.

in composition. This variation is illustrated in figure 20 in which the variation in the chemical composition is represented along the abscissa axis as weight percentages of lead oxide. The ordinates give then the values of the refractive index for sodium light, the ν-value, and the density for the glasses of the several compositions. Smooth curves passing through these points enable the observer to read off the percentage of lead oxide required in a glass having any desired constant represented on these curves. In figure 21 the changes in other optical constants (partial dispersions, ν-value) as well as in lead-oxide content, with change in refractive index n_D, are represented for all Schott and Chance flint and ordinary crown glasses. These

changes are represented in the flint series by smooth continuous curves. The diagram shows that the flint glasses are characterized by higher dispersions and a relatively more rapid rise in dispersion with rise in refractive index than is the case in the ordinary crown glasses.

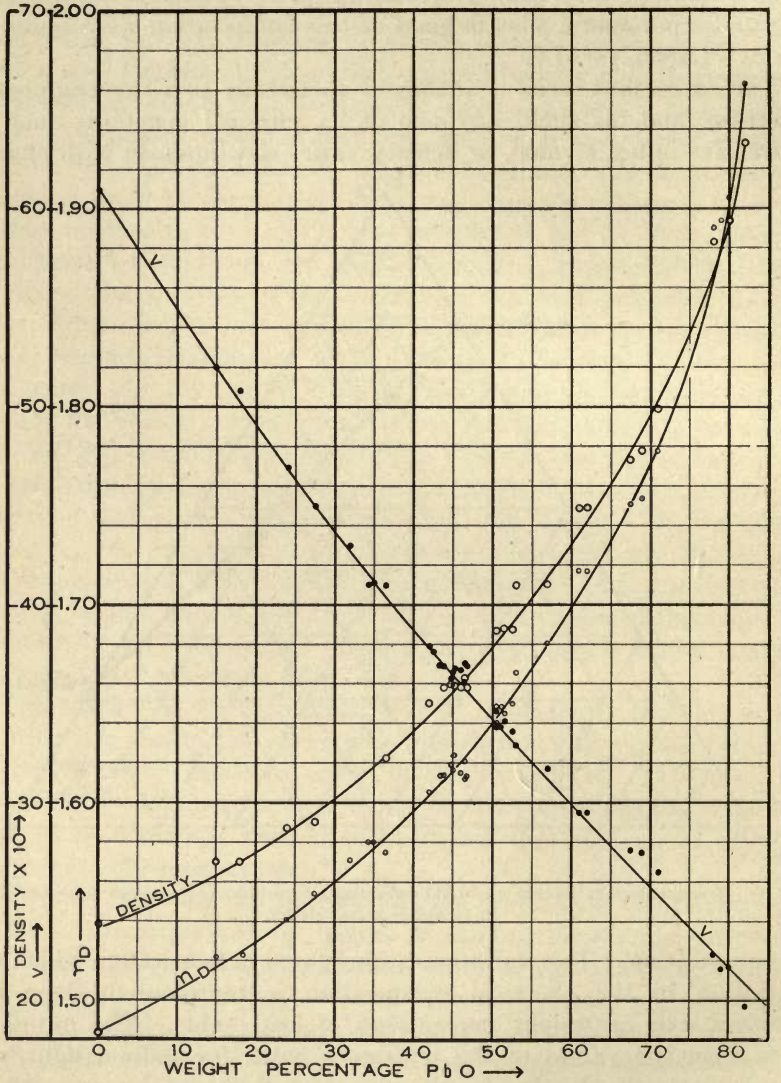

FIG. 20.—In this diagram there are shown the changes in the density and the optical constants (refractive index, n_D, and ν) with changes in lead oxide (PbO) in the flint series of glasses.

The foregoing three figures represent the sum total of empirical efforts on the part of glassmakers to produce a series of flint glasses which have certain optical properties. It is of interest to inquire, in passing, why the glassmakers, who did not know what figure 19

clearly demonstrates, should have chosen the particular compositions along the single straight line in the concentration field. The reason is not far to seek. Melts whose compositions lie above the line ap-

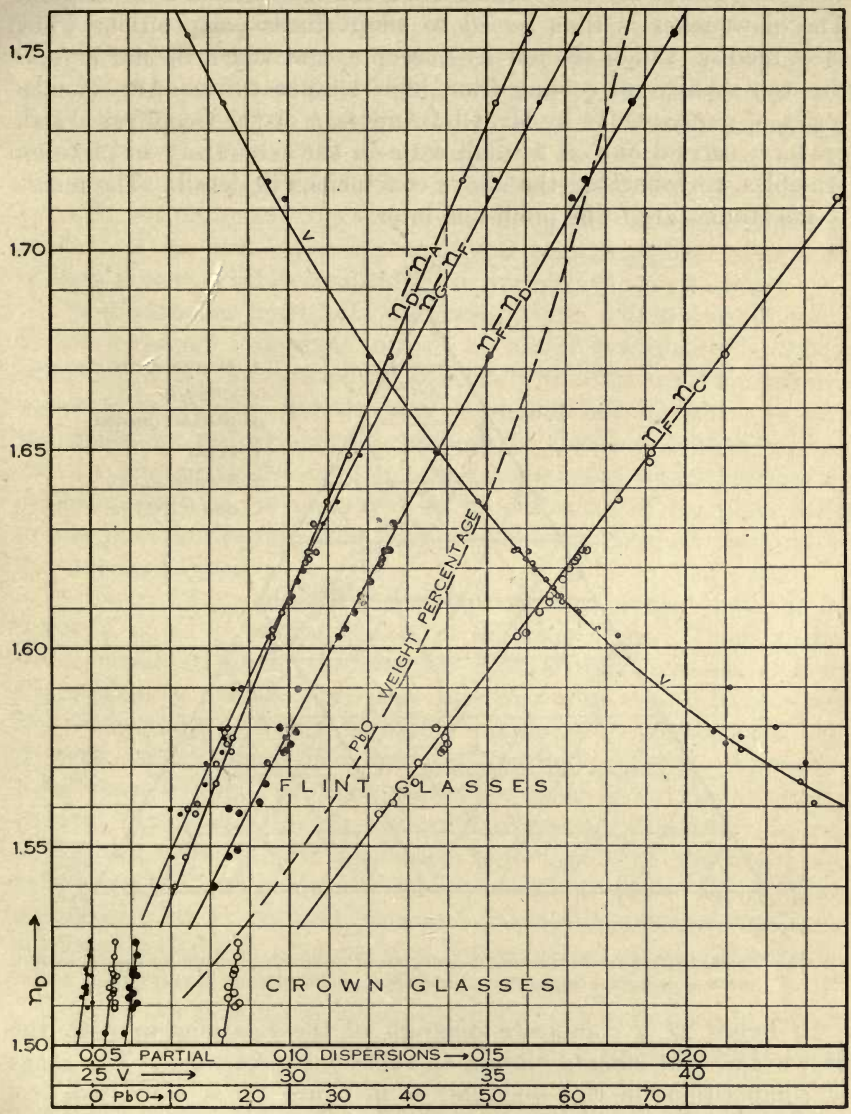

FIG. 21.—In this diagram the changes in the partial dispersions, $n_F - n_C$; $n_D - n_A'$; $n_F - n_D$; $n_C - n_F$, in the ν—values and in the lead oxide (PbO) content with changes in refractive index, n_D, are shown for the flint series of glasses. The ranges of partial dispersions in the ordinary crown glasses with changes in the refractive index, n_D, are also illustrated.

proach pure silica in composition and are extremely viscous and melt at such high temperatures that they can not be produced in furnaces of the ordinary type. Glasses whose compositions are given by points below the line approach either the alkalies or lead oxide in

composition. Glasses high in alkali melt easily, but are soft and extremely hygroscopic and therefore unsuitable for optical purposes. Glasses high in lead melt readily, but tend to crystallize with great ease and hence are unsuitable from the glassmaker's standpoint. The glassmaker is thus forced to adopt those compositions which melt readily, which are not hygroscopic, and which do not crystallize too readily on cooling from high temperatures. An extended series of experiments by Mr. Olaf Andersen of the Geophysical Laboratory, carried out on a small scale in the laboratory in platinum crucibles, corroborated the above conclusions in detail. The results of his studies are to be published later.

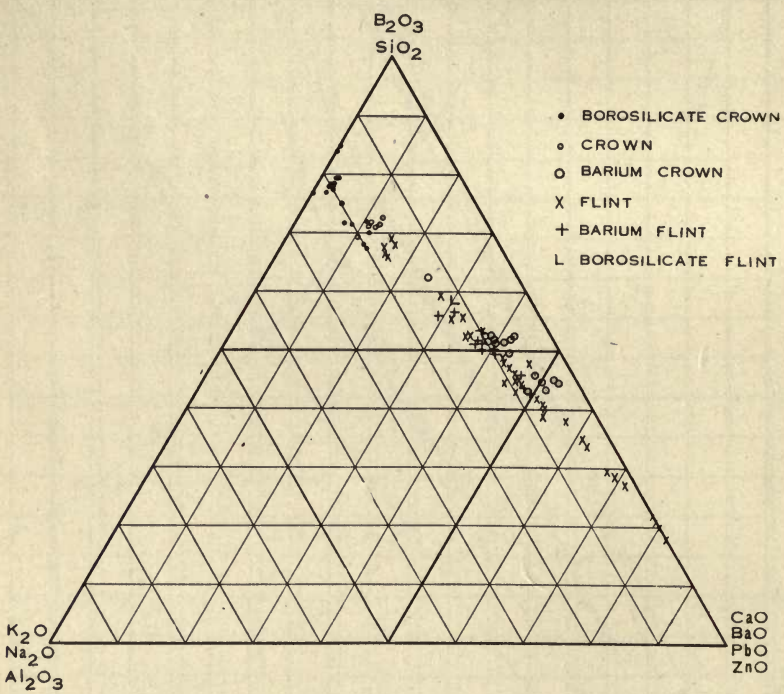

FIG. 22.—Triaxial diagram showing the weight-percentage compositions of the ordinary crowns, borosilicate crowns, barium crowns, flints, barium flints, and borosilicate flints of Table 4.

In figure 22 a composite diagram of the relations in both the crown and flint silicate glasses of Table 4 is presented. The range of compositions in this diagram, as in figure 19, is restricted to a fairly definite band; the reasons for this narrow belt of compositions are given in the foregoing paragraph. Although there is more leeway here for the glassmaker in the matter of compositions, there are certain definite limits beyond which he may not pass without inviting trouble and loss.

At the time we entered the war, a certain few of the optical glass types had become standard and sufficed for the optical instruments

required by the Army and Navy; our task consisted essentially in reproducing these types. The first problem was to devise and to develop manufacturing processes competent to meet the situation. The importance was realized of producing optical glass of uniformly high quality in which the departures from the standard types are negligible. The lens manufacturer can not afford to change his grinding and polishing tools with each pot of glass received in order to cope with large changes in optical properties which may occur from melt to melt. It is the task of the manufacturer of optical glass so to control his manufacturing processes that large departures from the standard type do not occur and the variations in optical constants from melt to melt of the same type are small and negligible; like other tasks of high precision these conditions are not always easy to meet.

The glassmaker must hold his glass to type within narrow limits. This is obtained from melt to melt by use of raw materials of high chemical purity, by controlling accurately the furnace temperatures, by using chemically and thermally resistant pots in which to melt the glass, by proper stirring methods to insure thorough mixing, also by adding to the molten batch ingredients which change the optical properties (as measured on proofs taken of the glass melt) in the direction required to have the finished product conform to the standard type.

In Figure 23 are plotted the variations in refractive index n_D for series of melts of optical glasses of different types. These glasses were furnished before the war by Schott und Genossen and by Parra-Mantois to an American manufacturer and indicate how closely in these specially favorable examples the melts were held to type. Each point on a curve of refractive indices represents a different melting. In other glasses the melts do not run so closely to type. In general, the glasses manufactured in this country showed at first somewhat greater departures from type than the European; but during the later months of the war after batch materials, quality, and treatment of melting pots and furnace conditions had been improved and placed on a basis of better factory routine the variations were no greater than in the European glasses.

An interesting series of measurements of the variations in refractive indices of optical glass fragments broken from different parts of the same melt was made by J. W. Gifford,[22] who found differences of 0.00033 in the case of a dense barium crown; as a rule the differences were restricted to the fifth decimal place.

In general, the refractive index of a glass type may vary from pot to pot by several units in the third decimal place; with certain glasses, such as borosilicate crown, the departure from type is less and restricted practically to ± 0.001; the ν-value may vary several

[22] Proc. Roy. Soc., 87, 189, 1912.

units in the first decimal place. First-quality glass selected from any one pot should be constant in refractive index within several units in the fourth decimal place; in some pots the difference between extreme limits may be 0.0008, but commonly they are less

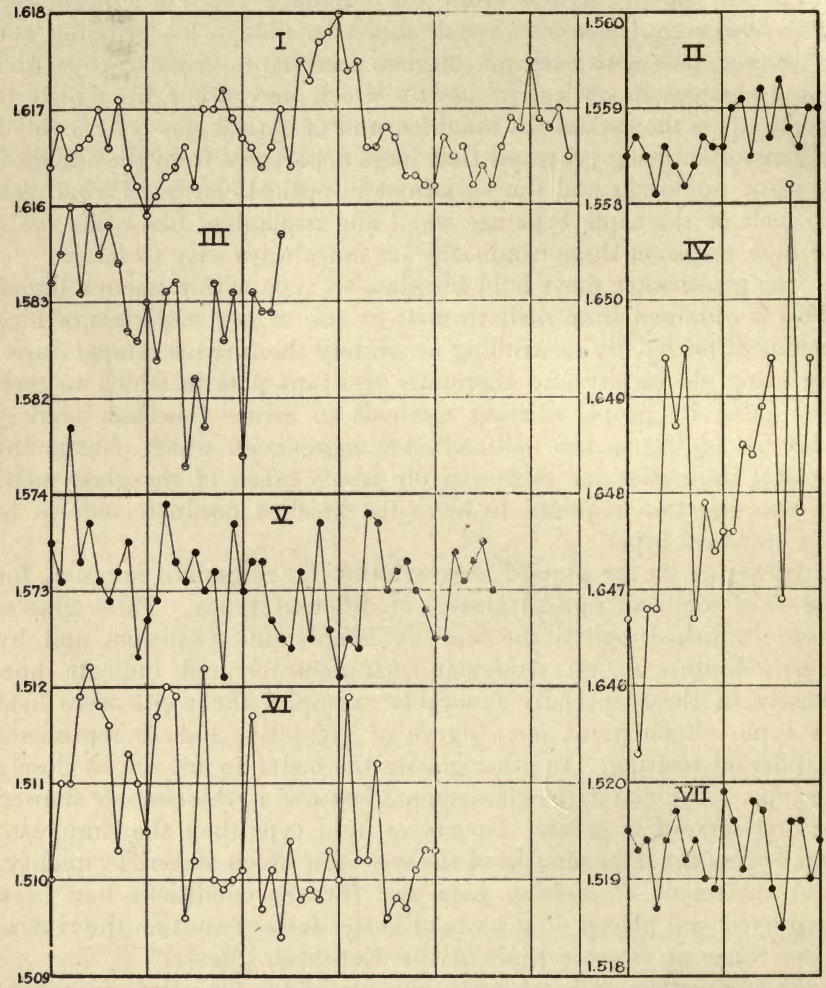

FIG. 23.—Curves illustrating the variations in refractive index, n_D, from pot to pot of melts of the same type as furnished by Parra-Mantois and by Schott and Genossen. These particular types show the smallest variations of a number of different types from which the selections were made. In each case all the melts of each type selected are plotted on the diagram. Each point on a curve represents a different melt. The types represented by the curves are: (I) Medium flint, n_D=1.6168, Parra-Mantois; (II) light flint, n_D=1.5587, Parra Mantois; (III) barium light flint, n_D=1.5825, Type O 578, Schott and Gen.; (IV) dense flint, n_D=1.6489, Type O 102, Schott and Gen.; (V), barium silicate crown, n_D=1.5726, Type O 211, Schott and Gen.; (VI) borosilicate crown, n_D=1.5100, Type O 144, Schott and Gen.; (VII) borosilicate crown, n_D=1.5163, Type O. 3832, Schott and Gen.

than this. The refractive index of a distinctly striated portion of the glass may and commonly does differ from that of the surrounding glass only in the fourth decimal place. The refractive index of a stria is commonly lower than that of the adjacent glass.

The optical constants of the principal types of glass produced at the several plants in the United States during the war are listed in Table 5. In this table only the more important types are included. The list could be increased manyfold if the variations or departures from type were included. This factor had to be taken into account in the specifications for optical glass furnished to the Army and Navy because in the early months of the war great difficulty was experienced in obtaining satisfactory melting pots which were thermally and chemically resistant. The difficulty arising from a wide range in refractivities of glass types was overcome to some extent by dividing the glasses of each general type into lots so that the range of refractivities in each lot was relatively small; the variations within the lot were then within the tolerance limits set by the manufacturer of the particular optical instrument for which the glass was intended. Under the stress of war activities this procedure was not always observed, and manufacturers received glass which necessitated changes of tools and consequent retardation of production. In war time the importance of competent personnel to handle such details can not be overemphasized; the lack of appreciation of the significance of technical details of this nature causes loss of time and money and may become serious in a crisis.

TABLE 5.—*List of optical constants of principal glass types manufactured in quantity in the United States during 1918.*

Manufacturer.	n_D.	ν.	$n_F - n_C$.	n_C.	n_F.
BOROSILICATE CROWN.					
Bausch & Lomb Optical Co.	1.5164	64.9	0.00795	1.51423	1.52218
	1.5190	64.6	.00803	1.51659	1.52462
	1.5171	64.3	.00804	1.51470	1.52274
	1.5100	63.5	.00803	1.50801	1.51604
Bureau of Standards	1.5244	64.0	.0082	1.5219	1.5301
Keuffel & Esser	1.51010	63.8	.00799	1.50734	1.51533
	1.50960	63.2	.00807	1.50717	1.51524
Pittsburgh Plate Glass Co	1.51579	63.8	.00807	1.51345	1.52152
	1.51611	63.6	.00812	1.51358	1.52170
	1.51300	62.3	.00823	1.51056	1.51879
Spencer Lens Co	1.51123	63.4	.00806	1.50884	1.51690
	1.51905	60.7	.00854	1.51646	1.52500
	1.51358	62.5	.00822	1.51107	1.51929
	1.51587	64.0	.00806	1.51340	1.52146
ORDINARY CROWN.					
Bausch & Lomb Optical Co	1.5116	61.0	0.00839	1.50923	1.51762
	1.5143	60.7	.00847	1.51191	1.52038
Bureau of Standards	1.51979	60.9	.00850	1.51530	1.52380
Keuffel & Esser	1.51593	60.8	.00849	1.51530	1.52194
Pittsburgh Plate Glass Co	1.52495	59.1	.00887	1.52170	1.53057
	1.52400	58.8	.00890	1.52135	1.53026
Spencer Lens Co	1.51635	60.6	.00851	1.51388	1.52239
	1.52389	59.5	.00880	1.52114	1.52994
Bausch & Lomb Optical Co	1.5699	57.0	.01000	1.56699	1.57699
	1.5721	56.8	.01006	1.56920	1.57926
	1.5710	56.5	.01010	1.56805	1.57815
Bureau of Standards	1.5728	57.7	.0099	1.5699	1.5798
Keuffel & Esser	1.57485	57.4	.01002	1.57198	1.58200
	1.57167	56.9	.01003	1.56880	1.57883
Pittsburgh Plate Glass Co	1.57718	56.1	.01040	1.57405	1.58445
	1.56100	57.7	.00968	1.55816	1.56784
	1.59300	54.5	.01088	1.58979	1.59300
Spencer Lens Co	1.57222	57.5	.00994	1.56925	1.57919
	1.56822	57.1	.00992	1.56529	1.57521

TABLE 5.—*List of optical constants of principal glass types manufactured in quantity in the United States during 1918*—Continued.

DENSE BARIUM CROWN.

Manufacturer.	n_D.	ν.	$n_F - n_C$.	n_C.	n_F.
Bureau of Standards	1.62149	53.6	0.01159	1.61809	1.62968
Spencer Lens Co	1.59500	57.2	.01040	1.59182	1.60222
Pittsburgh Plate Glass Co	1.61100	56.7	.01077	1.60796	1.61873

LIGHT FLINT.

Bausch & Lomb Optical Co	1.5619	44.8	0.01253	1.55829	1.57082
	1.5725	42.7	.01342	1.56864	1.58206
	1.5664	42.6	.01331	1.56258	1.57589
	1.5802	41.4	.01413	1.57615	1.59028
Bureau of Standards	1.58484	40.5	.01439	1.58070	1.59509
Pittsburgh Plate Glass Co	1.57220	42.1	.01365	1.56817	1.58182
	1.56900	42.5	.01337	1.56508	1.57845
	1.57900	41.1	.01408	1.57499	1.58907
Spencer Lens Co	1.58069	41.1	.01414	1.57668	1.59082

MEDIUM FLINT.

Bausch & Lomb Optical Co	1.6150	36.8	0.01779	1.60998	1.62667
	1.6180	36.5	.01692	1.61331	1.63023
	1.6218	36.4	.01806	1.61695	1.63401
Bureau of Standards	1.6274	36.4	.0172	1.6225	1.6397
Keuffel & Esser	1.61252	37.9	.01615	1.60799	1.62414
	1.61573	37.6	.01634	1.61101	1.62735
	1.61660	37.5	.01646	1.61209	1.62855
Pittsburgh Plate Glass Co	1.61800	36.6	.01686	1.61321	1.63007
	1.61100	37.3	.01640	1.60638	1.62278
	1.62700	35.6	.01760	1.62192	1.63952
Spencer Lens Co	1.60536	37.9	.01596	1.60079	1.61675
	1.61098	37.0	.01650	1.60630	1.62280
	1.62037	36.4	.01704	1.61545	1.63259
	1.63317	35.1	.01808	1.62797	1.64605

DENSE FLINT.

Bausch & Lomb Optical Co	1.6465	33.9	0.01904	1.64095	1.65999
	1.6495	33.7	.01928	1.64428	1.66356
	1.6545	33.3	.01963	1.64906	1.66869
Bureau of Standards	1.65555	34.4	.01903	1.65019	1.66922
Keuffel & Esser	1.65174	33.8	.01925	1.64628	1.66553
Pittsburgh Plate Glass Co	1.63500	34.9	.01818	1.62982	1.64800
	1.64500	34.1	.01883	1.63961	1.65854
	1.66100	32.9	.02013	1.65527	1.67539
Spencer Lens Co	1.64015	34.6	.01853	1.63489	1.65342

BARIUM FLINT.

Bureau of Standards	1.55000	52.6	0.01040	1.54700	1.55740
Pittsburgh Plate Glass Co	1.60300	44.0	.01370	1.59910	1.61280
	1.60900	43.4	.01405	1.60495	1.61900
Spencer Lens Co	1.62210	38.2	.01628	1.61744	1.63372

EXTRA DENSE FLINT.

Spencer Lens Co	1.75614	27.2	0.02778	1.74839	1.77617

III. FREEDOM FROM COLOR.

Color in optical glass is caused by the presence of certain coloring agents, which are generally difficult to eliminate from the raw materials, especially from the sand that goes into the glass batch. Iron in appreciable quantities may also be introduced as a result of solution of the walls of the pot. Copper, nickel, cobalt, chromic

oxide, vanadium, or manganese may also be responsible for some of the coloration. A very small amount of certain of these oxides suffice to produce relatively intense coloration. Iron oxide is the chief source of trouble in this respect. In the ferrous-ferric state it produces intense green coloration, in the pure ferric state the resulting color is pale yellow.

Chemical analyses show that the best European glasses contain less than 0.02 per cent Fe_2O_3; if the iron oxide content exceeds 0.05 per cent the glass is colored noticeably green or yellow green. The exact hue produced by a given amount of iron oxide is different for different glasses; in the barium crowns the color is green to bluish green; in the flints yellow to greenish yellow; in borosilicates a relatively large amount of iron is required to produce decided coloration, which is then gray green or gray blue. The amount of iron contributed by the pot is a serious matter and may equal or exceed that contained in the raw materials. Analyses show that the clay used in the German pots contains less than 1 per cent; in the clays used in this country it is commonly over 2 per cent. It is probable that in some of the glasses slight traces of a coloring agent, such as cobalt, may be present and affect appreciably the color and especially the transmission of the glass; the definite percentage effects on transmission of alumina and of the colorless oxides, such as the alkalies, alkaline earths, boron oxide, and silica on the light-transmission is unknown.

Experience with glass containing small quantities of iron oxide has proved that the resultant color of the glass is largely dependent on the state of oxidation of the iron; thus a decidedly green colored glass, if melted in a platinum crucible heated in an electric resistance furnace, becomes practically colorless under these conditions of high oxidation. In case manganese be present, the color may even shift to a decided purple. The effect of different degrees of oxidation may occasionally be observed in glass broken from a large melting pot, especially near the top margin of the glass mass. In this peripheral portion the color of the glass may change rapidly from decidedly green to colorless to purple. The following analyses of two samples taken from a large pot of flint (calculated synthetic composition: SiO_2 46.4, PbO 45.8, K_2O 2.7, Na_2O 4.7, B_2O_3 0.33, MnO 0.075) in which these color differences appeared, prove that the amount of manganese oxide present is the same throughout the mass; the manganese is calculated in both samples as MnO; the state of oxidation was not ascertained.

1	MnO 0.065
2	MnO .063

1. A small piece of glass from the top surface of the melt ranging in color from nearly colorless to decidedly purple. E. T. Allen, analyst.

2. Sample taken 5 centimeters from the top surface of the melt; decidedly green in color. E. T. Allen, analyst.

The chief objection to a slight amount of color is the fact that it indicates a glass of relatively low transmission. Glass intended for prisms, in which the optical glass path is necessarily long, should be relatively less colored than glass intended for thin lens elements. The quality of optical glass with respect to color is best ascertained as it is broken from the melting pot and can be observed in pieces a foot or more thick. Under these conditions all glass is appreciably colored. The same phenomenon can be seen on window or plate glass which appears through the plate to be colorless, but, when viewed through the edges, it is relatively dark green or yellow or blue green.

IV. HIGH DEGREE OF TRANSPARENCY.

This implies freedom from coloring agents which tend to absorb an appreciable portion of the incident light. In the best European glasses the light-absorption ranges from 0.3 to 0.6 per cent per centimeter thickness of glass path. High transmission is attained primarily by the use of raw materials of high chemical purity and by melting the glass in chemically resistant pots under conditions of high oxidation. The use of decoloring agents is not to be recommended, because they commonly function by contributing to the glass a color complementary to the color which would otherwise be obtained, the resultant effect being neutral gray. By this method relative freedom from color can be had, but only at the expense of the light transmission.

High transparency in optical glass for military instruments is important because on it the brightness of the visual image depends and with it the ability of the eye to detect details of distant objects. The better the Army and Navy can see the more effective are they in the presence of the enemy.

The treatment of polished glass surfaces to reduce the amount of light reflected.—Two factors contribute toward loss of light in a given optical system for a given intensity of illumination of object. These are: (1) Absorption of light by the glass itself; (2) reflection of light from the surfaces of the lens and prism elements. Theoretically the second factor has a definite limiting value which is fixed by the refractive index of the reflecting glass. For vertically incident light this value is expressed by the Fresnel equation $\left\{\frac{n-1}{n+1}\right\}^2$, in which n is the refractive index of the glass.

In 1892 H. D. Taylor [23] discovered that old photographic lenses which had become slightly tarnished were faster than new lenses of the same aperture. Evidently the exposed surface was modified in some way such that it reflected less light than before. Taylor

[23] The Adjustment and Testing of Telescope Objectives, published in 1896 by T. Cook, of York, England.

experimented with the problem and found that by the use of certain chemicals he was able to decrease the amount of light reflected by a given glass surface. He did not, however, reveal the actual chemicals which were used except to state that hydrogen sulphide and alkaline sulphides reduced the reflecting power appreciably. Recently F. Kollmorgen [24] has been able, by treatment of glass surfaces, to decrease the amount of light lost in an ordinary flint or barium crown lens from 8 to 10 per cent to 3 or 4 per cent. Experiments of similar nature were also made by Dr. H. Kellner [25] and similar results were obtained.

In view of the importance of this matter for range finders, periscopes, and other military optical instruments a series of experiments was begun by Dr. J. B. Ferguson and the writer during the early months of the war. Unfortunately other matters prevented the completion of this task, but the results thus far attained are of interest.

Polished specimens of light flint glass of refractive index $n_D = 1.570$ were immersed in solutions of different concentrations and held ordinarily for 18 hours at 80° *C.* The experiments proved that with a given concentration of solution the surface change is a gradual process, and that, for the best results, time-temperature-concentration relations are required for each solution with each type of glass. With the light flint specimens the greatest reduction in reflecting power was obtained with a 1 per cent solution of acid sodium phosphate (NaH_2PO_4) acting for 18 hours at 80° *C.* Solutions containing $\frac{1}{2}$, 2, and 20 per cent of the salt were tried, but these reduced the reflecting power less. Other solutions nearly equal in effectiveness are: Phosphoric acid (H_3PO_4), 1 per cent; copper sulphate ($CuSO_4$), 2 per cent; nickel sulphate ($NiSO_4$), 2 per cent; ferric sulphate ($Fe_2(SO_4)_3$), 2 per cent with a little free H_2SO_4; potassium dichromate ($K_2Cr_2O_7$), 2 per cent; less effective are solutions of potassium arsenate, sodium arsenate, copper chloride, zinc chloride, nickel chloride, cobalt chloride, potassium iodide, copper nitrate, acetic acid, potassium chromate; little, if any, effect was obtained with solutions of ferric nitrate, magnesium sulphate, zinc sulphate, copper chlorate, potassium chlorate, potassium sulphocyanide, potassium fluoride. Solutions of alkali salts, such as sodium carbonate, sodium bicarbonate, potassium carbonate, ammonium carbonate, etch the surfaces but do not decrease the reflecting power to any extent. In solutions of sodium sulphide and potassium sulphide a sulphide film is formed on the polished surface.

It is an interesting fact that the light reflected from a treated surface is in most cases appreciably colored; this color is commonly

[24] Trans. Soc. Illuminating Engineers, 2, 220–234, 1916.
[25] Private communication.

a faint blue or blue violet, but in the case of samples treated in solutions of potassium bichromate, copper nitrate, borax, potassium arsenate, the color of the reflected light is noticeably yellow.

Specimens of borosilicate crown glass were treated in similar manner and showed similar decreases in reflecting power. Good results were obtained with solutions of ferric sulphate, 1 and 2 per cent; copper sulphate, 2 per cent; potassium bichromate, 4 per cent; less satisfactory are solutions of copper nitrate, acetic acid, borax, potassium binoxalate, nickel sulphate, acid sodium phosphate. The time of exposure in all these experiments was 18 hours at 80° C.

Samples of light barium crown glass were found to be readily attacked. Weak solutions of nickel sulphate, acid sodium phosphate, copper sulphate, ferrous sulphate, phosphoric acid, acetic acid, copper chloride were tried; in all cases a decided decrease in reflecting power was observed, but the surfaces were noticeably etched, indicating too long exposure.

To account for this phenomenon of decreased reflection below the theoretical limits three tentative hypotheses are suggested:

1. A thin surface film of very low refractive index is deposited on the reflecting surface (adsorbed film).

2. There is selective solution at the surface such that the refractive index of the exposed residual surface is greatly lowered.

3. In the process of etching by the attacking solution the surface becomes covered with minute pits which are small compared with the wave length of light. Light waves impinging on the reflecting face encounter a plateau surface consisting of the remnants of the original polished surface with the intervening air pockets above the etch pits. As a result the etched surface behaves optically in its reflecting power as a material whose reflectivity is equal to the sum of the reflecting powers respectively of the exposed plateau elements of the glass, and of the intervening air spaces which are so small that they do not cause appreciable diffraction of the light waves.

The changes in the intensity of normally incident light on reflection with change in refractive index of the reflecting medium as computed by means of the Fresnel equation are listed in Table 6.

TABLE 6.—*Percentage of optically incident light reflected from a single polished surface.*

Refractive index of glass surface.	Per cent.
1.222	1
1.329	2
1.418	3
1.502	4
1.575	5
1.648	6
1.720	7
1.790	8
1.857	9
1.927	10

These computations indicate that a glass surface reflecting only 2 per cent of vertically incident light must have a refractive index 1.329, which is less than that of water.

The fact of the lowering of reflecting power by treatment in solutions is established beyond question. The change produced is so permanent that it does not disappear on ordinary rubbing or cleaning the surface or after several years' exposure to the air. Such surfaces show a tendency to appear faintly colored (blue or violet) in reflected light depending on the solution employed and also on treatment (polishing) just before immersion in the solution. If the refractive indices of original and treated samples are measured by total reflection methods no difference in refractivity between them can be detected.

The three hypotheses cited above are not of equal probability. The fact that the reflecting power can be lowered by immersing the glass surface in solutions of widely different character, and that the surface can not be rubbed off is difficult to explain by the first hypothesis. The refractive index required theoretically to give such low reflecting power, and the fact that the index of silica glass is about 1.460 is an argument against the second hypothesis. In favor of the third hypothesis is the observed change in refractive index of the zeolites and some other water-bearing compounds, namely, that on loss of water, the refractive index of the mineral is lowered and not raised as one might possibly expect.

During the war this process of treating polished surfaces to reduce the reflecting power was not developed to the point where it could be adopted as a routine factory operation; before this can be done more experimental data are required. The possibilities, from both a theoretical and a manufacturing viewpoint, are, however, great, and warrant further detailed investigation of this subject.

V. HIGH DEGREE OF STABILITY, BOTH CHEMICAL AND PHYSICAL.

The glass should be of such composition that it is weather resistant, does not tarnish readily, and retains an optical polish well. For most types of glasses this condition obtains; but in a few types, such as certain dense barium crowns and the borate and phosphate glasses, the lack of stability may cause trouble if the lens elements are not adequately protected from attack. Glasses high in alkalies are much less stable than glasses low in alkalies. Hardness and toughness are also a function of the chemical composition and of the state of annealing of the glass. The glass should be hard and tough, so that under ordinary field conditions the exposed surfaces are not easily scratched and damaged.

Experience with glasses in the Tropics has shown that the high temperature and humidity existing there are potent factors in

attacking exposed surfaces of optical glass in instruments. In optical instruments used in the Tropics a brown-colored film or coating may form which gradually dims the image and finally renders the instrument useless. Investigation of this coating has proved that in certain crown glasses crystals of sodium carbonate are formed on the polished lens surfaces; in other glasses an organic mold or growth or film scum appears, especially on instruments which have been sealed and made water-tight. This film may consist of many small liquid drops and occurs especially on the reticules of field glasses and fire-control instruments; in most cases it appears to avoid the area immediately adjacent to the etched lines of the reticule; or it may be much finer and spread uniformly over the polished surface. Experiments have shown that film of this nature is for the most part not an inherent defect of the glass itself, but is organic matter which has evaporated from lacquer and grease and dirt left in the instrument during the assembling process. The remedy for such film is meticulous care and cleanliness in the assembly of optical instruments. In certain cases the glass surfaces are badly attacked and the glass itself is then of faulty composition.

The stability of optical glasses is a difficult property to define satisfactorily. In all cases a glass is desired which shall remain unchanged on exposure to all kinds and conditions of weather. To test the stability of the glass under actual conditions is obviously a time-consuming process. The attack on the glass is, however, accelerated by elevating the temperature and the pressure. As a measure of the stability the behavior has been taken of the glass under arbitrarily fixed but reproducible conditions of high temperature and high pressure in acid, neutral, and alkaline solutions of known composition. There is danger, however, that the character of the reactions which take place at higher temperatures and pressures may be, and probably is, different from that of the reactions at room temperature and atmospheric pressure, with the result that the conclusions drawn from the behavior of the glass at high temperatures, high pressures, and concentrated solutions may be much in error when applied as criteria of the weathering stability of glass. For this reason it has been deemed better to devise tests of extreme sensitiveness which may be used at ordinary temperatures and atmospheric pressure. These and other tests will be described in Chapter IV on the inspection of optical glass.

Chapter III.

THE MANUFACTURE OF OPTICAL GLASS.

THE ORGANIZATION OF AN OPTICAL GLASS PLANT.

Optical glass has been shown to be a product which must meet the strictest demands of extremely high precision and throughout all stages of its manufacture this fact must be recognized. One of the chief difficulties encountered in the rapid development of optical glass manufacture in this country for war purposes was the lack of appreciation on the part of manufacturers, of superintendents, of foremen, and of workmen of this fundamental fact; to educate them to a proper realization of their several responsibilities required time and this necessarily retarded production during the first months of the war. High precision means careful control over all steps of the manufacturing processes and a personnel competent to establish such control; the problem is essentially one of physical and chemical engineering, and the manufacture of optical glass to be successful must be directed by men thoroughly trained along these lines. Technical control of this kind soon pays for itself in the quality and the quantity of the product obtained.

An optical glass plant should be so organized that effective control is exercised over each step of manufacture from the raw materials to the finished product. The raw materials should be of uniformly high chemical purity. They should be ordered from manufacturers under definite specifications and with provision for adequate chemical control at the factory to insure the necessary quality. The melting pots require close attention. If the size of the glass plant warrants it, each plant should have its own pot house; this obviates the inevitable jolts and jars and rapid changes in temperature and in humidity incident upon transportation and makes it possible to develop pots which are best suited to special types of optical glass. The melting and annealing furnace temperatures must be held to schedule. The batches must be properly mixed and filled into the pots. The crucible after removal from the furnace must be so cooled that properly fissured glass results. The inspection of the raw glass must be carefully supervised, otherwise much good glass is butchered and wasted, and much poor glass is taken into work which later has to be discarded. The molding and pressing of the glass into blocks must be properly directed, otherwise serious losses are incurred.

In the present chapter the several sections of the glassmaking process will be considered briefly and somewhat in the order of actual manufacture. In the analysis of these steps we shall find that there are many factors involved, and that only with proper regard to their several effects can optical glass of uniformly high quality be produced. In other words, the making of modern optical glasses does not consist solely in the mixing together of a secret batch, handed down from father to son, in melting this down in a furnace, and in allowing the melt to cool properly. In many branches of the glass industry there is still much that harks back to the days of the alchemist; many glassworkers are highly skilled artisans trained to their tasks from childhood; but in the making of optical glass there is little room for the deftness and whim of the artist. The problem is essentially one of precision and factory control; and although the glassmaker's experience is not to be disregarded, optical glass of high quality can not be produced by it alone. The training and the viewpoint of the chemist and physicist are required in addition to attain and to maintain the high quality of product essential for use in optical instruments for military purposes. A physicist or chemist is in a better position to undertake the manufacture of optical glass than is the plate or window glass maker of many years' experience who has fixed ideas on the subject of all glassmaking and can not realize that optical glass is different from the product which he has been accustomed to make.

In the management of an optical glass plant, as in all other industrial organizations, it is highly essential that each man and woman connected with the plant realize the importance of his or her work, and that the service rendered is contributing directly to the success of the plant and to the welfare of each individual in it. In time of war the spirit of active and wholehearted cooperation should dominate the entire plant and is easy to attain by proper appeal to patriotic motives and to the feeling that each worker is contributing his share toward the weal of the country in the emergency. In order that the organization function properly it is essential that the duties of every position be adequately prescribed, together with the responsibility and authority pertaining to the position. Workers should be selected and assigned with reference to their several capacities; those who show special aptitude and ability should be given opportunity to advance and to realize that their efforts are appreciated. Tact is required at all times to keep the organization running smoothly and effectively. During war time there is liable to be more or less continuous increase in personnel and equipment to meet the demands for more rapid production; also frequent changes in details of factory practice and routine to improve the manufacturing processes; it is necessary therefore to keep the organization of the plant so flexible

that, without fundamental changes in its structure, it can take care of the changing demands made upon it. This means, among other tasks, the training of some of the workers for more than one particular task.

There are many factors which enter into the problems confronting the management of an organization of diverse human elements and which have to be considered if the desired end is to be attained, namely, high-speed production, together with a satisfied and effectively cooperating and loyal group of workers. It would lead too far in this report to consider further this most important of all factors, namely, the human factor, without which nothing can be done in spite of the best and most improved processes of manufacture. Suffice it to state that in an emergency, such as war, nearly everyone is eager to do his part, or may be compelled to do so, and to that extent the problems are simplified.

RAW MATERIALS.

In the foregoing pages reference is made to the many factors which enter into the manufacture of optical glass; of these not the least is purity of raw materials. Except for certain gases, such as carbon dioxide, nitrogen oxide, oxygen, water vapor, etc., which are liberated during the fusion process, and for the small amounts of certain somewhat volatile oxides, such as lead oxide, which escape during the melting and fining stages, whatever is put into the batch appears in the final product and can not later be eliminated; this fact makes it imperative for the glassmaker to use batch ingredients of high and definitely known purity. Optical glass is unfortunately sensitive both in color and in refractivity to slight changes in chemical composition. If the glassmaker neglects to insure proper quality and uniformity of raw batch materials, not only is the glass produced variable and unsatisfactory, but the furnace schedule may be seriously affected and production all along the line to the finished optical instrument is impeded and rendered uncertain.

The best procedure to reduce to a minimum the variations in composition and quality of the raw materials is to establish direct contract relations with the producer of the raw materials (not with the jobbers), each contract to state explicitly the kinds and amounts of impurities which may be tolerated. Each shipment of raw material should be analyzed at the plant with reference to impurities and to water content. The batches are then computed on the basis of this analysis; if this procedure is not followed, an element of uncertainty is introduced which, in certain types of glass, may cause a departure from the desired optical constants sufficiently large to render the glass useless for the purpose for which it was intended.

Much time and effort was spent by the Geophysical Laboratory in canvassing the raw material situation throughout the country, in developing rapid routine methods for the testing of such materials, and in educating manufacturers to a realization of what high chemical purity in large lots means. To obtain raw materials of adequate purity, it was necessary for the Geophysical Laboratory to make many tests and analyses of samples submitted, to send men to different places to examine the methods of production, to suggest changes in method in order to insure proper quality, and to encourage manufacturers to install special apparatus to meet the demands for high chemical purity. The standards required for optical glass are extremely high, and it means very accurate and direct analytical control at the plant to obtain a product of proper quality. In particular, the sand situation and the potassium carbonate situation required close attention.

Sand.—The requirements of sand for optical glass are high chemical purity and uniform, small size of grain. High chemical purity is essential because silica constitutes the major part of most optical glasses. The iron content of the sand should be less than 0.02 per cent iron oxide. The water content of each sand shipment should be determined. Other coloring agents such as chromium, manganese, vanadium, copper, cobalt, etc., should not be present. Most of the sands in this country contain more than 0.02 per cent iron oxide; but with careful selection of the sand at the quarry it is possible in several of the localities to obtain sand of a degree of purity better than 0.02 per cent iron oxide. Experience has shown that sands suitable for optical glass are located at Rockwood, Mich., Hancock, Md., and Ottawa, Ill. These deposits are all of friable sandstone deposited under wind-blown, desert conditions during early geologic times (Lower Paleozoic). Of these three deposits, the Rockwood sand is the purest; the best grade contains on an average about 0.015 per cent iron oxide. The sand is pure white and remarkably uniform in size of grain. Optical glass of good quality can be made from the sand of any one of these three localities. [1]

An extended series of experiments was carried out by the Geophysical Laboratory with a view to extracting the iron from the sands and chiefly from the glass melting pots by chemical means. For this purpose the sands and pots were submitted at high temperatures to an atmosphere of chlorine gas; under these conditions the chlorine attacks the iron oxide and forms iron chloride, which is volatile. This reaction takes place much more rapidly and completely if, in place of chlorine, phosgene gas (carbonyl chloride) is used. The final outcome, however, of these experiments, which were intensely

[1] See Notes on American high-grade glass sands, by P. G. H. Boswell, Trans. Soc. Glass Technology I, 147-152, 1917.

interesting from a laboratory viewpoint and extended over many months, has been that it is not worth the while in war times to attempt the purification of sands on a large scale by such methods. The expense of the chlorination process is, moreover, relatively high, and sufficiently pure sand is available in the open market. Methods for the determination of iron in glass sand are described by J. B. Ferguson, jr.[2]

Potassium carbonate.—Before the war the better grades of potassium carbonate were imported from Germany. It was not a difficult task at that time to obtain potassium carbonate of the desired degree of purity. This source of supply, however, was shut off, and it was necessary for manufacturers to develop new sources and to arrange for the purification of potassium carbonate on a large scale. At the earnest solicitation of the Geophysical Laboratory, the Armour Fertilizer Works, of Chicago, Ill., patriotically undertook to produce the quantities of potassium carbonate of the required purity for optical glass. This they were able to do after some months of experimentation, and the supply of potassium carbonate after that time was assured. During the early months of the war it was necessary to obtain the potassium carbonate in small, odd lots from jobbers and to analyze each cask. Much of this potassium carbonate contained appreciable quantities, up to 5 per cent, of potassium and sodium chloride and sulphate. The presence of these salts was most unwelcome in the light flint-glass batches, and at first a number of melts were lost because of the fact that the glass turned milky on cooling, thus rendering it useless for optical purposes. It was found necessary in each lot of potassium carbonate to determine the amounts of water, of sulphates, of chlorides, and of iron present in addition to potassium and sodium content. Methods of analysis were developed which enabled these determinations to be made rapidly and accurately. The potassium carbonate furnished by the Armour Co. was in crystallized form (K_2CO_3, $2H_2O$) and contained about 18 per cent water of crystallization. The SO_3 content averaged between 0.2 and 0.4 per cent, the chlorine content between 0.1 and 1 per cent, that of iron oxide from 0.01 to 0.02 per cent.

In view of the scarcity and high cost of pure potassium carbonate, efforts were made to reduce its quantity in the batches and to substitute for it sodium carbonate and to use a larger quantity of potassium nitrate which was readily obtainable in a relatively pure state. These efforts were entirely successful and it was found that, if in the batches, sodium oxide (as sodium carbonate) is substituted in amounts equal in weight percentage to that of the potassium oxide, the optical constants (refractive index, n_D, and ν) of the glass are changed but little; the refractive index is raised slightly and the

[2] J. Ind. and Eng. Chem., 9, 941, 1917.

ν is lowered slightly. The glass, however, tends to be somewhat duller in appearance and at high temperatures is slightly less viscous than the original potassium melt; for this reason greater care is required in the annealing of soda-rich glasses. This substitution of sodium carbonate for potassium carbonate and the use of relatively larger amounts of potassium nitrate materially reduces the cost of the batches.

Sodium carbonate.—Experience has shown that sodium carbonate sufficiently pure for all purposes can be obtained in the open market. It should contain less than 0.01 per cent Fe_2O_3, 0.03 per cent SO_3, and 0.4 per cent H_2O.

Calcium carbonate.—Precipitated calcium carbonate appears to be the best and purest source of calcium oxide. Certain marbles, such as that from Rutland, Vt., are also satisfactory. The Fe_2O_3 content should not exceed 0.05 per cent and preferably be less than 0.01 per cent.

Barium carbonate.—Precipitated barium carbonate of high purity and with an iron content less than 0.01 per cent is produced by several firms in this country. The presence of sulphur compounds in this material is not desirable as they tend to color the glass. Some chlorine may be present, but it should be less than 0.05 per cent in amount.

Lead oxide.—Lead oxide in the form of red lead (Pb_3O_4) or of litharge (Pb O) containing less than 0.02 per cent iron oxide was obtained only with difficulty. Sublimed litharge was found to contain the least amount of iron oxide. In flint glasses there is some danger of reduction of the lead oxide to metallic lead; the furnace conditions must accordingly be oxidizing and abundant nitrate should be present in the batch.

Boric acid.—Boric acid and borax are obtainable without difficulty and in a sufficiently pure state; also zinc oxide, alumina, and arsenious oxide.

Specifications for the degree of purity of the raw material for optical glass are based on the observations that for glasses of high transparency the amount of iron oxide Fe_2O_3 present should not exceed 0.02 per cent; chlorine, 0.6 per cent, and SO_3, 0.1 per cent; nickel oxide should not be present. Part of the iron oxide in the glass is derived from the batch materials and part from the solution of the walls of the melting pot. A series of analyses, by J. B. Ferguson, of the iron oxide in the raw batches for different types of optical glass and the finished glasses made from these batches proved that in pots of good quality from 15 to 30 per cent of the total iron oxide present in the glass is contributed by the pot; in pots of inferior quality the percentage contributed by them is of course higher. The batch should therefore contain less than 0.015 per cent iron oxide and perferably less

than 0.01 per cent. For many of the batch materials, such as KNO_3, K_2CO_3, $NaNO_3$, Na_2CO_3, $B(OH)_3$, ZnO, a specification of 0.01 per cent Fe_2O_3 in the oxide itself is easy to meet but in others this is not the case and for these materials reasonable limits should be set which the manufacturers can meet without difficulty. In no case, however, should the percentage of Fe_2O_3 exceed 0.05, otherwise the total percentage of Fe_2O_3 in the glass may exceed 0.02 and the resulting transparency be unsatisfactory. To determine the percentage of Fe_2O_3, allowable in a salt, such as sodium carbonate Na_2CO_3, in order that the Fe_2O_3 in the oxide Na_2O shall not exceed 0.01 per cent the ratios in Table 7, page 106, are convenient; thus for Na_2CO_3 the Fe_2O_3 content should not exceed 0.0058 per cent.

One of the chief results flowing from this need for high chemical purity of raw materials was the realization by certain manufacturers of what must be done in order to obtain the desired chemical purity, and the establishment in their works of methods of high precision. Our experience along these lines proved clearly in many instances that the need for such factory control had not been realized by manufacturers. To meet the situation, these manufacturers adopted scientific methods of procedure and their products were then equal in every respect to the best European products.

MELTING POTS.

The art of pot making, like that of glassmaking, has been until recently in the hands of a chosen few, who learned their trade in childhood from their fathers and who have guarded most jealously their acquired knowledge. In recent years, however, the characteristics of the different clays and other materials which enter into the composition of pots have been studied in ceramic laboratories and there is now available a considerable amount of information regarding the clays of this country and their thermal and chemical behavior. At the time when we entered the war great difficulty was experienced in obtaining pots of proper quality and a number of melts were lost because the molten glass dissolved its way through the pot. The clays, which were then used, contained on an average about 2 per cent of iron oxide with the result that, no matter how pure the batch materials were, the solution of a thin film of the inner walls of the pot 1 millimeter thick increased the percentage of iron in the melt from 0.02 to 0.04 per cent, and the finished glass had a decidedly green or yellow color. Through the efforts of several pot makers, especially the Laclede-Christy Co., the Buckeye Clay Pot Co., the Gill Clay Pot Co., the Willetts Clay Pot Co., and, in particular, Dr. A. V. Bleininger, of the Bureau of Standards,[3] with the cooperation of the United States Geological Survey, clays and kaolins relatively

[3] Jour. Am. Ceram. Soc., I, 1–23, 1918.

free from iron and highly resistant have been located in this country and pot mixtures have been developed which approach pure kaolin in composition. They contain little if any free quartz and are satisfactory in nearly every respect.

The qualities desired in a glass melting pot are resistance to chemical corrosion by the molten glass, freedom from iron oxide, and ability to withstand exposure for a day at least to temperatures of 1,450° to 1,500° *C* without deformation even when filled with heavy molten glass. A clay pot is necessarily heavy and weighs from 500 pounds to a ton or more; its walls range from 2 to 6 inches in thickness, depending on its size and material. Extreme care is taken during

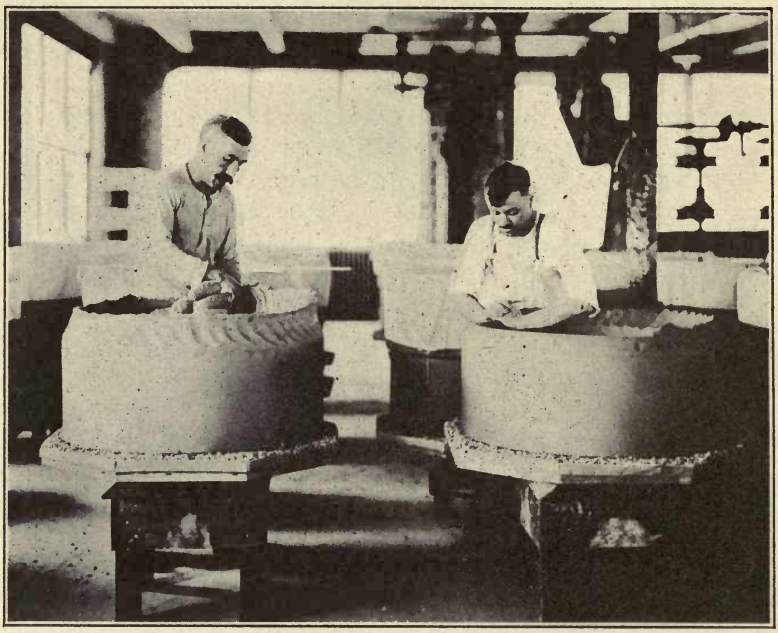

FIG. 24.—Clay pots in the making by the hand "building-up" process. (Photograph by J. Harper Snapp at the plant of the Bausch & Lomb Optical Co.)

the drying-out process to avoid the development of small shrinkage cracks because these weaken its strength and furnish entrance channels for the molten glass batch to attack its walls, thereby inviting disaster. The same degree of care is exercised on heating a pot to a high temperature; this operation requires ordinarily three to five days. At all stages of this process the glassmaker seeks to attain uniform heating of the entire pot and to avoid direct contact of the heating flame at any one point which then would become superheated and eventually cause the pot to crack.

Glass melting pots can be made up either by the old building-up process (fig. 24) or they can be cast or poured into molds. The cast pots have an advantage over the ordinary type of pot in that they

are more dense and dry out more quickly. The ordinary type of pot requires from three to six months to season, whereas the cast pot of the porcelain-kaolin type is ready for use within two months or less. It is outside the domain of the present report to enter into a detailed discussion regarding the manufacture of these pots. They can now be had commercially from several different firms and there is no reason to fear that in the future such pots will not be available. In war time it is, of course, essential that the output be regulated properly and that standard types of pots only be used.

The pots commonly employed for optical glassmaking during the war period were open pots and measured 36 inches outside diameter by 32 inches high (27 inches inside diameter and 27 inches deep). Still smaller pots, 30 inches outside diameter and 23 inches high, were used at first as a makeshift; still larger pots, 49 inches outside diameter and identical in size and shape with the standard ton plate-glass casting pot were successfully employed, especially by the Pittsburgh Plate Glass Co.

A method for casting pots of the porcelain-kaolin type was developed during the war by A. V. Bleininger [3] at the Bureau of Standards in Pittsburgh. In these pots broken waste bisque of white-ware potteries, which is relatively free from iron, served as "grog" and the composition of the pot as a whole approached kaolin with only a small amount of iron oxide present; in them dense barium crown glass was melted successfully. Unfortunately these pots were not available in quantity during the war and were not used to any extent in the production of optical glass for war purposes. The advance which this new process marks is, however, great and much credit is due Dr. Bleininger for having placed it on a satisfactory basis.

Open versus closed pots.—Manufacturers are not in accord regarding the use of closed pots in the manufacture of optical glass. The greater part of the optical glass in this country is made in open pots, averaging 36 inches in diameter and holding about 1,000 pounds of ordinary crown glass or 1,500 pounds of dense flint glass. So far as can be ascertained from the literature, European practice favors the use of closed pots. The reason for this is obvious. In the open pot the glass melt is exposed to the direct gases and vapors of the furnace; these may be reducing in action, even though the general run of the furnace has an excess of oxygen. This is especially true on windy days when the air supply is more or less irregular. On such days gusts of smoky gas full of soot can be seen sweeping over the pot. There is consequently danger in open pots of reduction phenomena which may seriously affect the quality of the product. A still further objection to the use of open pots is the fact that there plays across the top of the pot an incessant current of gas; this gas consists of several

[3] Jour. Am. Ceram. Soc., I, 1–23, 1918.

kinds of vapors which are more or less soluble in the glass melt; moreover, a current of gas passing over the exposed surface of the melt blows away the vapors of alkalies or lead oxide and this increases their rate of volatilization; on turning off the gas to allow the pot to cool down, the vapors over the pot are entirely changed; certain absorbed gases may then tend to escape and thus give rise to bubbles which are difficult to eliminate at this stage of the process. Furthermore the uncovered pot is open to a larger space of the furnace, and vapors, absorbed or indigenous, on escaping, may tend only slowly to reach a vapor pressure comparable to their saturation pressure for the given temperature and compositions.

The covered pot is protected from the reducing influences of heating gases; there is no circulation of gases over the surface of the melt which tend to sweep the components of the melt away and to accelerate their rate of evaporation; there is no abrupt change in vapor pressure and in composition of the vapors above the surface of the melt on turning off the gas, or on removing the pot from the furnace. The covered pot tends toward uniformity in the cooling of the melt as well as toward keeping the melt homogeneous; the tendency of the uncovered pot is in the opposite direction.

The uncovered pot on the other hand is heated in furnaces of the regenerative and recuperative type, chiefly by radiation from the crown of the furnace, and as a result heats up more rapidly and more efficiently than the covered pot in which the heat has to penetrate through the walls of the pot in order to reach the melt. This rapid rate of heating is not to be underestimated, because by it the time required to melt and to finish the glass is much less than that required when covered pots are used. The glass-melting process even in open pots of ton size in the plate-glass industry takes less than 24 hours. In the manufacture of optical glass the complete melting process may also be finished within 24 hours, thus allowing a melt to be finished in the furnace in one day. With covered pots, such a time-schedule of furnace operations is not possible.

During the war open pots or semicovered pots were used in this country even for the production of extra dense flint and dense barium crown glasses. The results prove that the open pot is satisfactory for the melting of any of the ordinary types of optical glass, such as are required in military optical instruments.

The bleaching of pots.—During the early months of the war the available pots were of poor quality and relatively soluble in the optical glass melts; they contained several per cent of iron oxide; some of this iron was dissolved by, and entered into the melt, coloring the glass green and lowering its transparency; the absorption of the glasses ranged from 2 to 5 per cent per centimeter as compared with 1 per cent or less of the European glasses. It was realized that if the iron oxide

could be removed from the walls of the clay pot in contact with the melt, other conditions remaining the same, one source of serious trouble would be eliminated. An extended series of experiments was accordingly made by the Geophysical Laboratory on the action of chlorine gas on the walls of an empty pot at high temperature; this method was based on the known fact that at high temperatures iron chloride is very volatile. Similar methods had moreover been used before for removing iron from enamels [4] and also from small crucibles [5] and from other materials.

To convert the iron contained in the walls of the clay pot into volatile iron chloride both chlorine and phosgene gas were tried; phosgene gas is chemically much more active than chlorine gas, especially at its dissociation temperature (slightly below 600° C.). The pot to be bleached was placed in a pot arch or melting furnace and in most instances was covered with a clay lid; a continuous stream of chlorine gas was then allowed to flow into the crucible for a given period of time (one-half hour to five hours) at temperatures ranging from 400° to 1,250° C. Much iron (up to 80 per cent) was removed by this treatment and the walls of the crucible were bleached to a depth of 15 millimeters; the rate and effectiveness of the reaction increased with the temperature; crystals of iron oxide (hematite) were deposited in great numbers along the outer edge of the pot where the escaping iron chloride gas entered the furnace chamber.

In spite of the marked decrease in iron content of the pot walls, a corresponding decrease in the iron content of the glass melted in the treated pot was not observed and, in one instance at least, the glass was full of pot stones. The chlorine-gas treatment, by dissolving the iron oxide which formed part of the bond of the clay pot, had evidently rendered the walls of the pot more porous and less resistant to attack. It is possible that subsequent baking of the pots after the chlorination treatment would restore the compact structure of the walls as a result of sintering and incipient melting. This situation and the rapid improvement in the quality of the pots at this time stopped further experimentation along these lines. It is better to use pots having a low initial iron content, to bake them thoroughly at very high temperatures, and to shorten the melting period than to attempt to purify the clay in the finished pots and thus to run the risk of spoiling an entire melt because of stones derived from the loosened pot wall texture.[6]

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[4] Bole and Howe, Trans. Am. Ceram. Soc. 17, 125 (1915).

[5] G. C. Stone, cited in Jour. Am. Ceram. Soc. 2, 360 (1919).

[6] A detailed description of the experiments on the use of chlorine gas for the volatilization of iron from optical glass pots is given by Hostetter, Roberts, and Ferguson in Jour. Am. Ceram. Soc. 2, 356–372, (1919).

FURNACES.

For the manufacture of optical glass three different types of melting furnace are in common use; of these two are of the reverberatory type and operate either on the regenerative (fig. 25) or recuperative principle, the air in them being preheated by the hot products of gas combustion escaping from the furnace chamber. The third type is a non-regenerative, stackless furnace, heated by a blast; in it the air-gas mixture is injected into the furnace under pressure. In the regenerative and recuperative furnaces the heating of the crucible is accomplished chiefly by radiation from the crown of the furnace. This in-

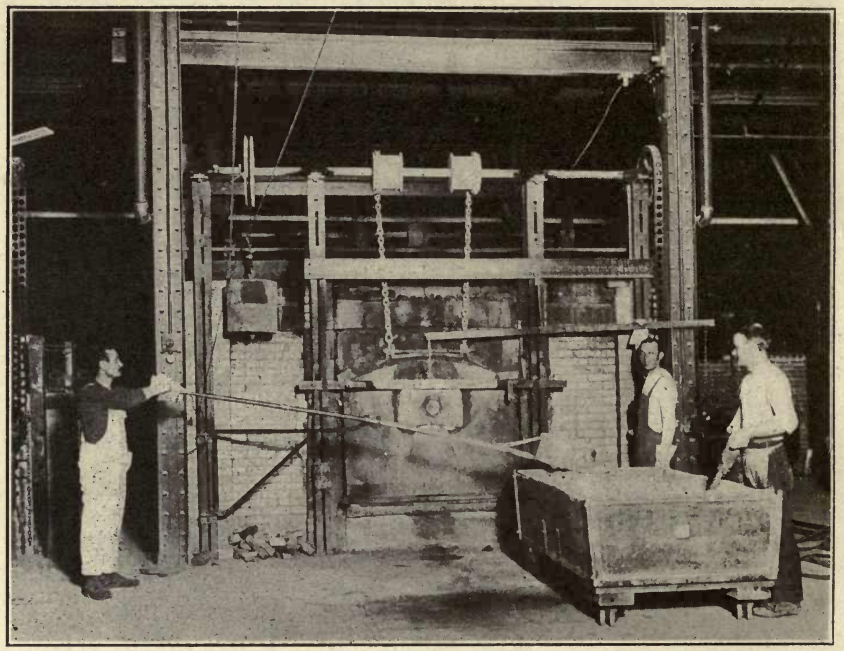

FIG. 25.—Batch about to be filled by means of long "scoop" into glass-melting pot inside the furnace. (Photograph by J. Harper Snapp at the Bausch & Lomb Optical Co.)

sures a more even distribution of heat than in any type of furnace in which the combustion of the gases takes place within the furnace itself as in the blast furnace. Experience has shown, however, that good optical glass can be produced in any one of these types of furnaces, provided they are properly regulated, both with respect to temperature control and to gas combustion. Whatever type of furnace is available, two factors are fundamental to the production of good optical glass, namely, maintenance of a definite temperature over a long period of time, and constancy of temperature distribution within the furnace chamber so that the melting pot is uniformly heated.

Because of the careful regulation of furnace conditions required in optical glass making, it is common practice to use single-pot melt-

g furnaces of dimensions adapted to fit the size of pot used. Dur-
g the war pots 36 inches outside diameter were commonly used and
generative furnaces with a chamber measuring 4½ by 5 by 5 feet,
side dimensions, were found to be satisfactory. (Fig. 25.) In these
rnaces a heavy door (tuille), suspended by chains and capable of
ing raised by a hand crank, closes the front of the furnace. The
ille in turn has a smaller opening through which the batch is intro-
ed and later the stirring rod enters. Ordinary fire clay serves to
aster up the cracks between the tuille and the brickwork of the
rnace. At one of the plants (Bausch & Lomb) several two-pot
rnaces of the regenerative type were erected and proved to be
ccessful; these furnaces were equipped with tuilles at each end.
operating a two-pot furnace special care must be taken to insure
niformity of furnace conditions. Batches of the same composition
d pots of the same size must of course be used in any given run in
two-pot furnace. On the whole there is no special advantage
gained by the two-pot furnace except that it occupies less space than
the two single-pot furnaces.

It is not germane to the present report to discuss the details of construction of optical glass making furnaces. It is assumed that the builder of such a furnace has considered the type of furnace, the materials for its construction, the best design and size of chamber, the kind of fuel available (natural or artificial gas), the size of stack, and the best arrangements for the combustion of the gas. Suffice it to state that for ease of regulation and general efficiency the regenerative and recuperative types of furnace are superior to the other types. The single-pot regenerative type is considered to be the best.

It is the task of the furnace man, assigned to a furnace of given type, so to run it that the desired temperatures are attained and maintained and that within the furnace chamber an oxidizing atmosphere is always present, especially in the vicinity of the pot of molten glass. Low, lazy, sooty flames sweeping over the surface of the molten metal are to be avoided, as they indicate a reducing atmosphere. On windy, gusty days such flames are almost inevitable, but the furnace operator should be on the alert to reduce their occurrence to a minimum.

In the regenerative type of furnace the flow of gas should be reversed at definite intervals in order to insure uniform temperatures; if, through carelessness, the furnace gets out of balance and one side is colder than the other, fluctuations of 50° C. with each reversal of the flow of gas within the furnace may arise. The balance is restored by allowing the cooler checker work of the furnace to be heated for a longer period of time than that of the hotter side.

Measurement of furnace temperatures.—Different methods are in use for ascertaining furnace temperatures. Formerly this was done

by the furnace operator who, from long practice and often with no protection for his eyes, estimated with remarkable accuracy the furnace temperature by direct inspection. To the untrained observer the furnace at the melting temperatures is at "white heat," and no details are distinguishable within it; however, with the aid of dark glasses to reduce the intensity of the light and heat radiations, he can readily see the details, but can not estimate the temperatures satisfactorily. The human eye is not infallible and even the expert furnace man may make costly mistakes which would not have occurred had better methods for temperature measurement been used.

In the ceramic industry Seger cones are employed, while in the glassmaking industry thermoelements are in general use and are placed in the rear wall of the furnace where they indicate continuously the temperature of the hot junction of the thermocouple; the cold junction of the thermocouple is kept at constant temperature either by burying it from 6 to 10 feet in the ground at some distance from the furnace or by immersing it in a pail of water attached to the rear wall of the furnace where it is held at the constant temperature of boiling water. The thermoelement in this position does not indicate the actual furnace temperature, but the temperature of the point within the furnace wall to which it extends. As a result, there is an appreciable lag in its readings of the fluctuations of temperature within the furnace. The exposure, moreover, to the furnace gases which penetrate into the retaining tube causes the thermoelement to deteriorate and to give readings which are too low and inclined to be somewhat erratic. More satisfactory are pyrometers, optical and electrical, which enable the observer to ascertain the actual temperature of any point within the furnace.

A portable standard thermoelement of platinum and platinum rhodium with compensating leads can be used if properly shielded from the furnace gases. A device of this sort for purposes of investigation was devised by the writer (Report No. 4 for week ending May 26, 1917) and was constructed by leading the thermoelement wires through a water-cooled iron pipe 10 feet in length to a porcelain tube 18 inches long, closed at one end, and attached to the end of the pipe; the porcelain tube is made of highly refractory material, and is about 1 centimeter in outside diameter. (Fig. 26.)[7] The cold junction of the thermoelement is held in ice and the electromotive force of the couple is read off on a direct-reading millivoltmeter. By means of this water-cooled thermoelement rod, temperatures at different points within the melting furnace and pot arches were ascertained and compared with the temperatures measured at the same time and on the same points by the Morse optical pyrometer

[7] Reproduced from article on optical pyrometers by C. N. Fenner in Bull. Am. Inst. Min. and Met. Eng., 1006, 1919.

(Leeds and Northrup type) and the Féry radiation pyrometer (Taylor Instrument Co., type). To illustrate the distribution of temperature in one of the single-pot furnaces, the following readings were taken along the line extending from a small opening in the furnace tuille (door) to the rear wall of the furnace and over the crucible about 5 inches above the surface of the metal.

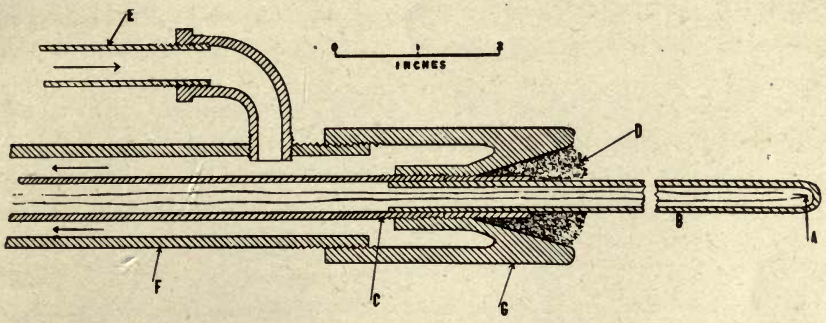

FIG. 26.—Sectional view of end of water-cooled temperature-measuring device. *A* is the hot junction of platinum-rhodium thermoelement; *B*, a refractory porcelain tube; *C*, inner iron pipe; *D*, asbestos packing; *E* and *F*, iron pipes of water-cooling system; *G*, specially turned iron terminus of water-cooling system.

Distance from outside of door.	Temperature.	
Feet.	° *C.*	° *F.*
0.5	1,222	2,232
1.0	1,273	2,323
1.5	1,287	2,349
2.0	1,365	2,489
2.5	1,373	2,503
3.0	1,386	2,527
3.5	1,396	2,545
4.0	1,403	2,557
4.5	1,403	2,557
5.0	1,403	2,557
5.5	1,398	2,548
6.0	1,395	2,543

These readings show that the temperature distribution above the pot itself is fairly uniform; near the furnace door there is of course an appreciable drop in temperature.[8] (Fig. 27.)

The thermoelement rod is satisfactory for exploratory purposes, but the porcelain tube at the end is too fragile for factory adaptation.

The optical pyrometer, on the other hand, is a satisfactory works instrument. It is essentially a low-power telescope, in the image plane of which a heated metal filament (small electric lamp) is viewed, together with the object whose temperature is to be ascertained. (Fig. 28.) Both image and filament are viewed through a red-colored glass, and the intensity of illumination of the lamp filament

[8] These measurements were taken by Dr. C. N. Fenner and the writer and are cited in the article on "The use of optical pyrometers for control of optical glass furnaces, by C. N. Fenner, Bull. Am. Inst. Min. and Met. Eng., 1006, 1919.

is changed until it practically disappears against the illuminated field. Since the intensity of luminous radiation varies with the fourth power

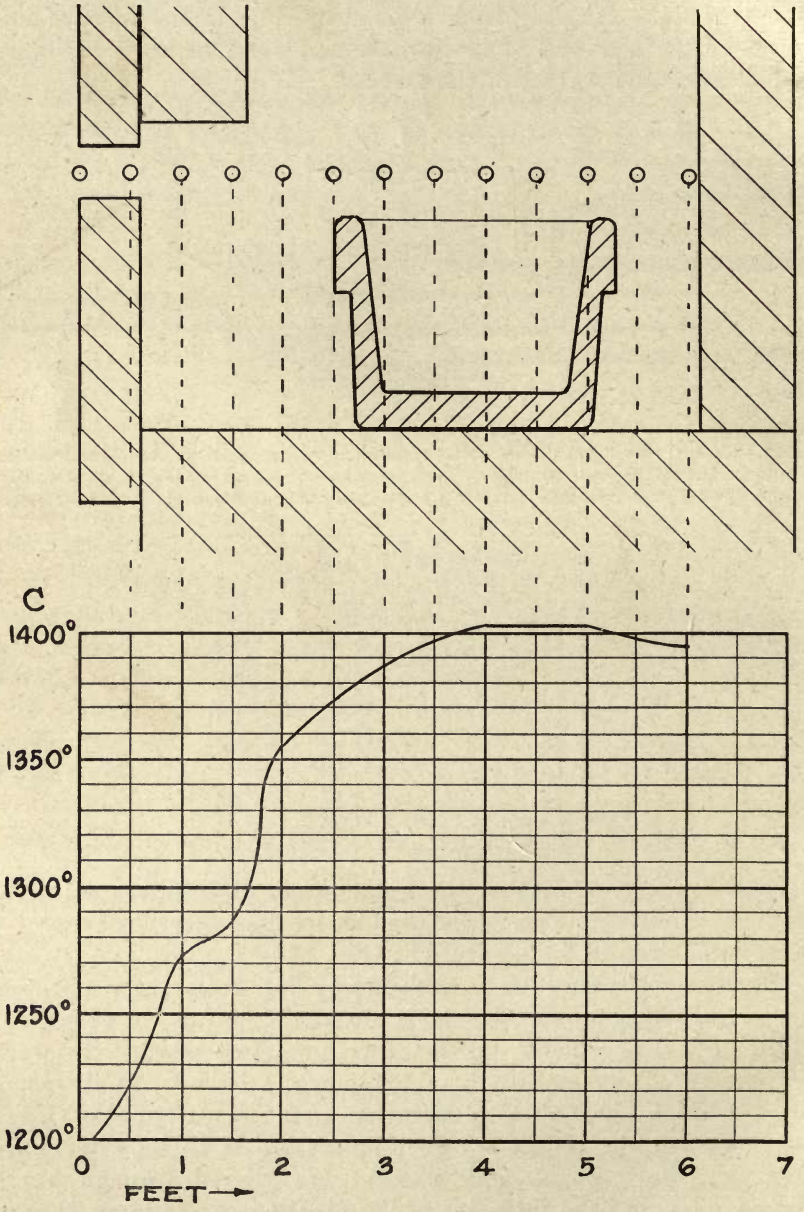

FIG. 27.—Cross section of melting furnace, showing points at which temperature measurements were made with the water-cooled rod of fig. 26. Below is the corresponding distance-temperature curve.

of the temperature (Stefan's law), a slight change in temperature suffices to produce a great change in the brightness of the furnace. The instrument is remarkably sensitive, and with it concordant

results are easily obtained by different observers, provided certain precautions are taken.

The instrument should be calibrated at stated intervals, because with use the characteristics of its electric lamp change and with them the temperature-indicating scale of the instrument. The calibration is readily accomplished by means of a standard thermoelement to read the temperature of the stoppered end of a porcelain or clay tube heated to definite temperatures either in the glass-melting furnace or in a laboratory electric-resistance furnace; a tube of this sort approxi-

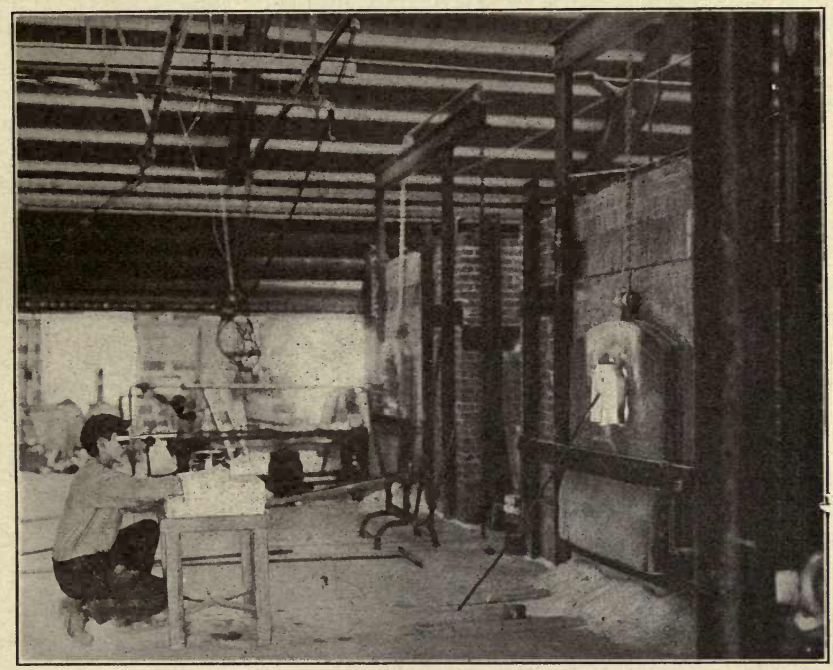

FIG. 28.—Photograph of operator measuring the temperature of optical glass-melting furnace with an optical pyrometer. The operator is regulating the resistance in order to match the intensities of lamp filament and furnace illumination. (Photograph by J. Harper Snapp at the Hamburg plant of the Spencer Lens Co.)

mates a "black body" in its characteristics and serves the purpose well. The heated inside of this tube is imaged by the telescope and the current reading of the lamp for this temperature is ascertained. A series of such readings for different temperatures suffices for the calibration.

Experience with the optical pyrometer has proved that it is well adapted for furnace work. At temperatures above 1,350° C. (2,450° F.) its readings, after proper calibration, are commonly in error less than 5° C. At temperatures from 950° to 1,050° C. (1,750° to 1,900° F.) there is a great difference in temperature between the

arch of the furnace, which is in direct contact with the burning gases, and the furnace walls which are heated by radiation; at these temperatures the readings of the optical pyrometer are invariably too high and average about 35° C. above the correct value. The walls reflect the light from the hotter crown of the furnace and consequently appear brighter and hotter than they actually are; the temperature of the rear wall of the furnace as determined by the optical pyrometer is moreover not so high by 10° or 20° C. as the side walls which have a better chance to reflect the light. These differences in apparent temperature between the rear and side walls of the furnace at 1,000° C. are readily detected by the unaided eye; on looking into the corner of such a furnace near the end of the stirring period of the glass the observer notices a distinct difference in the brightness of the side and rear walls at their junction. At these temperatures care must be taken by the observer to sight upon the same spot in the furnace each time in order to attain uniformity in the readings from melt to melt. Experience has shown that the most satisfactory results are attained at this stage of the glassmaking process, which immediately precedes the removal of the pot from the furnace, by sighting on the molten glass adjacent to the moving stirring rod. The glass at this point is hottest, and its surface is uneven and reflects light from all parts of the furnace.

In the radiation pyrometer the focal length of the gold-plated reflecting mirror is so short that at the focus not only is the object sighted upon imaged, but in the near vicinity (fraction of a millimeter) points several feet away are also imaged with the result that the radiation pyrometer tends to integrate the temperatures of points along the line of sight at some distance in front of and behind the actual point sighted upon. If the furnace approaches a black body in its temperature distribution, this is not a disadvantage; but where this is not the case difficulties arise which are apparently less easy to allow for than in the optical pyrometer.

It is convenient in all cases to use thermoelement pyrometers in conjunction with the optical pyrometer because they aid the furnace operator in following his schedule and serve as a check on the readings of the optical pyrometer.[9]

Furnace men after a certain amount of practice learn to estimate with some precision the temperatures within the furnace; but in all cases a careful record should be kept from hour to hour of the measured temperatures within each melting furnace in order that large fluctuations do not occur and seriously affect the quality of the glass.

[9] A detailed discussion of the methods found useful during the war for the measurement of the temperatures of optical-glass furnaces is given by C. N. Fenner, in Bulletin Am. Inst. Min. & Met. Eng., No. 151, pp. 1001–1011 (1919).

THE BATCHES.

The glassmaking industry has been one of slow development through the centuries from the time of the Egyptians and Phœnicians to the present day. It has been cultivated in certain restricted areas and has been handed down as an art from father to son, with the result that even at present it is enveloped in an air of mystery and secrecy. The formulas for making the different types of glass are held highly confidential and may not be divulged except to a chosen few. As a result the glassmaking industry is conducted with few exceptions by rule-of-thumb methods and the manufacturing processes are controlled by men of special experience who occupy unique positions in the factory. In Europe the optical-glass industry is no exception to this rule; all details of actual manufacture are closely guarded; but little has been published on the subject, and it is difficult to obtain reliable information of any kind. The batches for the several types of optical glass required by optical-glass manufacturers are not available, except for a few of the older types of optical glass.

In undertaking the manufacture of optical glass in this country it was necessary therefore to gather together such chemical information as could be found and to have analyses made of the more urgently needed types of optical glass which happened to be in stock. A statistical study of the available analyses was first made. This study, the results of which are given in Chapter II, was supplemented by experiments on the changes, during the melting process, in the relative quantities of the several chemical elements in the batch as a result of volatilization and of solution of the pot. Certain relations, particularly in the series of ordinary flint glasses and of the barium crowns and flints, were discovered which enabled us, by interpolation, to write down at once the batch for any member of their series such that the finished glass should have approximately the desired refractive indices and ν-values. Experimental batches were first made up in small quantities and melted down in pots containing 10 to 50 pounds. In this way we soon arrived at definite control over the entire series of desired optical glasses and were in a position to reproduce any one of the silicate glasses which was needed.

As a result of this statistical study, carried on under definite scientific principles, we became independent of all secret batches and were able to proceed to a scientific study of the relations between chemical composition and optical constants of the resulting glass and to determine in a general way the effect of any individual chemical element on the optical constants. This proved to be of great value, as it allowed us to devote our entire attention to the other factors on which the quality of optical glass depends.

Computation of batches from chemical analyses of glasses.—In preparing a batch to reproduce a glass of given optical constants it is necessary for the operator to take into consideration the losses incurred by selective volatilization of the batch components. The amounts lost during the melting and fining processes depend on the size and character of the batch, the character and temperatures of the furnace, the method of filling in the batch, the type of the melting pot, whether open, semiclosed, or closed, the duration of the operations, and the character of the stirring, so that it is not possible to give more than rough percentage estimates of these factors. A few experiments suffice, however, to determine the relations for a given set of operating conditions; once these have been ascertained the glassmaker endeavors to adhere to them strictly and thus to insure uniformity in the final product. In the computation of the batch mixtures the following allowances are made for losses by selective volatilization: PbO or Pb_3O_4, 0.5 to 5 per cent and even higher;[10] boric oxide, 1 to 5 per cent, in case boric acid rather than borax is used in the batch; the alkalies, K_2O and Na_2O, up to 5 per cent. Little definite information is available on the losses incurred by selective volatilization and in a given case much depends on the factors already mentioned. At the present time it is a matter largely of experience and of actual trial to make proper allowance for these factors. As a result of this volatilization the batch becomes relatively richer in silica and the refractive index of the finished glass is lowered. In the case of extra dense flint or dense barium crown melts volatilization becomes serious when melts are made in open pots. In this case the greatest care must be taken to keep the furnace conditions similar from melt to melt, otherwise large fluctuations in refractive index occur from pot to pot and these work a hardship on the manufacturer of lenses for which these glasses are used. If there is an appreciable solution of the walls of the pot, the alumina and silica thus dissolved tend to lower the refractivity of the glass. An effort should be made in all cases to reduce this uncertainty by employing melting pots which are both thermally and chemically resistant.

From the relations presented in foregoing paragraphs it is possible to prepare a plot from which the batch composition for any member of the flint series can be read off directly. (Fig. 29.) This plot is constructed on the basis of sand 100 units of weight (pounds or kilograms). Thus from the diagram the batch composition in kilograms for the flint glass of refractive index $n_D = 1.640$ we read: Sand, 100; lead oxide (PbO), 119, or (Pb_3O_4), 122; anhydrous potassium carbonate (K_2CO_3), 20.6; potassium nitrate (KNO_3), 7. Sodium oxide

[10] See O. Andersen, The volatization of lead oxide from lead silicate melts. Jour. Am. Ceram. Soc., 2, 784, 1919.

in the form of sodium carbonate or sodium nitrate may be substituted for potassium oxide provided the amount of Na_2O (weight percentage) equals in weight the amount of K_2O which it replaces; substitution of Na_2O for K_2O raises the refractive index slightly, decreases the ν slightly and changes the viscosity relations noticeably. Flint glasses high in soda exhibit a tendency to be duller, less transparent, and more noticeably colored than the corresponding pure potash flints. The density and ν of any glass of given PbO or Pb_3O_4 content are indicated on the plot (fig. 29) by the intersections of the PbO or Pb_3O_4 ordinate with the curves for density and ν respectively; thus in the foregoing example the density of the flint glass $n_D = 1.640$

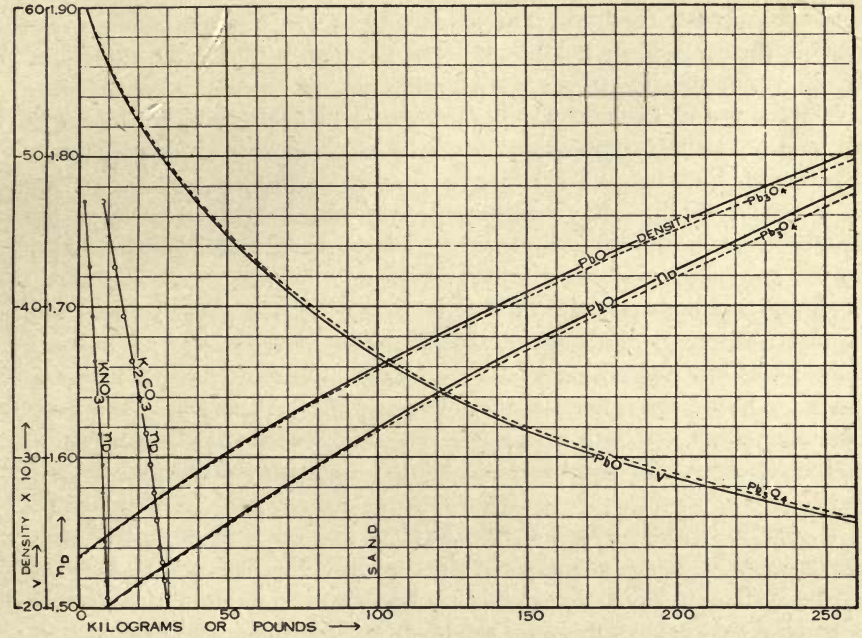

FIG. 29.—Batch-composition diagram for the series of ordinary flint glasses. The diagram is prepared on the basis of sand 100. From the diagram the approximate batch composition for any flint glass of given refractive index, n_D, or ν-value, or specific gravity, d, can be read off directly.

is $d = 3.78$ and its $\nu = 34.5$. The batch composition for a flint glass of $\nu = 46.0$ is, in kilograms: Sand, 100; PbO, 44.5, or Pb_3O_4, 45.5; K_2CO_3, 7.6; KNO_3, 2.2. Its density is 2.93 and its $n_D = 1.549$.

The compositions of glasses of other types can be ascertained by means of the compositions given in Table 4 (p. 59) together with the data plotted especially on figures 15 and 22, Chapter II. It would lead too far to consider these systems in detail; in some of them the information at hand is meager and hardly sufficient for satisfactory interpolation; but in most instances the glassmaker, with the aid of these methods and the data now available, is able to write down batches which approach very closely the batch desired, so that with a few

experimental melts in small crucibles he can determine the correct batch composition within very narrow limits.

The foregoing diagrams indicate clearly the fields which are dominated by the different oxides; in view of these relations it is, therefore, fitting to name the silicate glasses as had been done: Fluor crowns, borosilicate crowns, ordinary crowns, and barium crowns; flints, barium flints, and borosilicate flints. Zinc-bearing glasses do not require separate designation, because zinc oxide in optical glasses does not impart special optical properties to the glass; it serves chiefly to change the concentration and viscosity relations in optical glass melts, especially to render the melt easier to work and to decrease the tendency to crystallize on cooling. In the flint series the light, medium, and dense flints are distinguished. The barium flints are flints in which part of the lead is replaced by barium. In all types of silicate glasses the amount of silica present is relatively large and the optical characteristics of each glass are in effect a blend of characteristics between those of silica and some other end member or members with silica commonly dominating.

A study of the above diagrams, especially figure 15, page 50, proves that in the silicate optical glasses, lead and barium oxides on the one hand, silica and boron oxide on the other, exert the most profound influence on the optical constants of the glass. Thus the highly refracting glasses contain abundant lead oxide or barium oxide; the low refracting glasses contain abundant silica or boron oxide. Of all the glassmaking elements, lead has the most pronounced effect on both the refractive index and the dispersion; it increases especially the blue end of the spectrum relatively to the red.

If in a flint glass of given refractivity, a high ν-value (lower dispersive power) is desired, part of the lead oxide is replaced by barium oxide (introduced in the batch as barium carbonate). Compared with lead oxide, barium oxide produces less high refractive index and very much weaker dispersion (high ν-value); glasses high in BaO and PbO are called barium flints or baryta flints. Zinc oxide is intermediate in its action between calcium oxide and lead oxide on the one hand, and barium oxide on the other; like calcium oxide it tends to raise the refractive index and the dispersion slightly. In the series of flint glasses the relative dispersion increases with increase in refractive index; in other words, if, for the sake of comparison, the refractive indices n_A', n_C, n_F, n_G', for each member of the series are divided by the refractive index n_D, then the ratios increase with rise in refractive index n_D; the characteristic feature of the dispersion of lead glasses is the rapid rise in refractivity toward the blue and violet end of the spectrum. The same relations are

clearly shown in a diagram in which the ratios $\frac{n_D - n_A'}{n_F - n_D}$ and $\frac{n_G' - n_F}{n_F - n_D}$ are plotted as abscissae against the refractive indices as ordinates.

Increase in silica, boron oxide, or fluorine tends, on the other hand, to lower the refractive index, to increase relatively the dispersion of the red end of the spectrum and at the same time to decrease the total dispersion. This lengthening of the red end of the spectrum is especially true of boron oxide and apparently also of fluorine[11] in the fluor crown glasses. The addition or substitution of small amounts of boron oxide raises the refractive index of certain glasses slightly. This behavior is remarkable because by itself the refractive index of boric oxide glass is only $n_D = 1.463$ and $\nu = 59.4$; that of silica glass is $n_D = 1.4585$ and $\nu = 67.9$. Evidently borates are formed which impart different properties to the glass from those which might be inferred from the characteristics of the individual components.[12] Similarly alumina (Al_2O_3) which, in the crystallized state has a very high refractive index (1.76), produces with silica a glass of unexpectedly low refractivity. Alumina and magnesia raise the viscosity of most glass melts and tend thereby to prevent crystallization.

Phosphorus, although formerly used in appreciable amounts, especially in the series of phosphate glasses, has now been discarded because of the poor weather-resistant qualities of the phosphate glasses. Figure 15 shows that these glasses differ only slightly from the borosilicates and the barium crowns; this difference does not outweigh the practical disadvantage of weathering instability.

The essential differences between the ordinary flints and ordinary crowns are the higher refractivity and the greater dispersion, both actual and relative, especially in the blue end of the spectrum, in the flint glasses. With these two types of glasses it is not possible therefore to compensate exactly the dispersive effects of a positive crown element by a negative flint element and secondary spectrum results. By the use of glasses in which the relative dispersions are more nearly similar than between the crowns and flints, it is possible to correct more perfectly for achromatism; the presence of the two chemical elements, barium and boron, in optical glass shifts the relative dispersions in the crowns and flints so that they are more nearly in accord. By the use of these elements in the flint glasses the extreme dispersions of the blue end of the spectrum in the normal flint glasses are reduced relatively and the course of the dispersion throughout the visible spectrum is rendered more nearly like that of a crown glass.

[11] The statement made by Hovestadt, Jenaer Glas, p. 11, 1900, that boron oxide tends to lengthen the red end of the spectrum, whereas fluorine has the opposite effect and tends to decrease the red end relatively to the blue is apparently not borne out by the fluor crown glasses, which, however, contain abundant boric oxide and this may veil the effect of the fluorine.

[12] See also Zschimmer, Zeitschr. Elektrochemie, 11, 632, 1905.

In writing down the batch composition for a glass of specified refractive index and dispersion the glassmaker has a number of factors to consider, such as chemical composition and the changes in composition resulting from selective volatilization and from pot solution. In the series of ordinary crowns and flints, silica (sand), alkalies (potassium and sodium oxides), lime (calcium oxide), and lead oxide are the essential constituents; in these the proportions of the different elements may not exceed certain limits. If the percentage of silica is above 75 per cent the melt is so viscous that it can not be properly melted in the furnace; the percentage of alkalies may not exceed 20 per cent, otherwise the resultant glass is hygroscopic and chemically unstable; over 13 per cent of lime may not be used because of the tendency of melts high in lime to crystallize, and because of the difficulty of fusing such melts properly; lead oxide may be used up to 70 per cent or more, but in glasses containing a large percentage of lead the danger from crystallization and from attack on the melting pot is serious. In the new series of glasses, boron, barium, zinc, and aluminium oxides are the most important additional constituents which are employed; up to 50 per cent barium oxide may be used, but then ordinarily together with boron and alumina; melts high in barium attack the crucible seriously, especially if any free silica is present in the clay. The dense barium glass melts require, moreover, special furnace treatment to produce a glass free from bubbles and other defects such as crystallization nuclei.[13] Boron oxide may be used up to 20 per cent or more; it replaces in a measure silica. In general the use of small quantities of boric acid in lead glasses is not to be recommended, because experience has shown that its presence favors the development of opalescence in the glass on cooling. Zinc in quantities above 12 per cent is likely to cause crystallization of the glass. More than 5 per cent of alumina tends to render most glass melts exceedingly viscous and practically unworkable at the melting temperatures; in most glasses the presence of alumina decreases the danger from crystallization and renders the glass tough and resistant. In the densest barium crown glasses up to 10 per cent Al_2O_3 may be used; it aids not only in preventing crystallization of barium disilicate, but it also improves the working qualities of the melt and glass. The presence of chlorine or sulphur in the batch materials is to be avoided because of the danger of opalescence in the finished glass. In case these elements are present, it is advisable to run the melt at a very high temperature.[14]

[13] Compare N. L. Bowen. Jour. Wash. Acad. Sci., 8, 265–268, 1918; Jour. Am. Ceram. Soc., 2, 261–281, 1919.

[14] See J. D. Cauwood and W. E. S. Turner. Jour. Soc. Glass Techn., 1, 187, 1917; C. N. Fenner and J. B. Ferguson, Jour. Am. Ceram. Soc., 1, 468, 1918; C. N. Fenner, Jour. Am. Ceram. Soc., 2, 106, 1919.

The presence of arsenic in most glasses is favored by many glassmakers because it tends to increase the transparency and brilliancy of the glasses; certain experiments indicate that the presence of arsenic in the melt probably sets up an oxidizing action at high temperatures [15] and thus reduces the effect of iron as a coloring agent. Although some arsenic is volatilized in the melt yet an appreciable amount remains in the solution. Careful analytical work by Allen and Zies [16] of the Geophysical Laboratory has demonstrated the presence in optical glasses of arsenic in both states of oxidation, as arsenic trioxide and arsenic pentoxide. They consider that the chief function of arsenic may be to cause a "boil" and thus to sweep out small entrapped bubbles which otherwise rise with extreme slowness to the top; they found that in green plate glass in which no nitrate is used much more arsenic escapes from the melt than from a melt such as spectacle crown glass containing niter. R. L. Frink [17] observed crystals of arsenious oxide in bubbles in glass, thus proving that at the high temperatures this oxide is volatrilized from the melt. Allen and Zies conclude "that arsenic trioxide is oxidized at low temperature and the product formed is stable enough to remain until a high temperature is reached and the glass becomes fluid, when it slowly dissociates into oxygen and arsenic trioxide, both of which aid in the fining."

Fenner [18] adds the suggestion that the large bubbles of arsenic vapors may in addition collect potential bubbles by functioning as vacuum chambers into which volatile substances may evaporate at a rapid rate. Be the effect what it may the general practice is to add a little arsenic to the batch and the results attained by its use warrant its continuance as a component of optical glass batches.

In the preparation of batches the nitrates and carbonates of the alkalies are used in proportions ranging from 1:5 to 1:2, depending on the type of glass; nitrates alone produce too active a melt, while carbonates alone do not furnish the desired oxidizing agents. Melts high in alkalies and made from batches containing alkali carbonates, but no nitrates, are difficult to fine properly. The chief function of alkalies in optical glass is to produce melts which are easily workable; they influence the viscosity of the melt; the viscosity of a potassium flint glass melt changes very slowly with the temperature; that of a sodium flint glass changes fairly abruptly at a temperature somewhat above the softening point. Increase in the total alkali content of a glass commonly raises its refractive index slightly; thus in the medium flint glasses an increase in alkalies with corresponding decrease

[15] See Doelter, Handbuch der Mineralchemie (Leipzig), **1**, 861, 1912; also E. T. Allen and E. G. Zies, Jour. Am. Ceram. Soc., **1**, 787, 1918.

[16] Jour. Am. Ceram. Soc., **1**, 767–794, 1918.

[17] Trans. Am. Ceramic Soc., **17**, 798, 1915

[18] Jour. Am. Ceramic Soc., **2**, 123–124, 1919.

in silica, the percentage of lead oxide remaining the same, raises the refractive index. Both alumina and magnesia may exert a profound effect on the viscosity of the melt. In the computation of batches from chemical analysis the data of Table 7 are useful.

TABLE 7.—*Table of molecular weights and ratios between molecular weights for use in the computation of glass batches from chemical analyses.*

MOLECULAR WEIGHTS.

Al_2O_3	102.2	Fe_2O_3	159.7	Sb_2O_3	288.4
As_2O_3	197.9	K_2O	94.2	SnO_2	141.0
BaO	153.4	Li_2O	29.9	TiO_2	70.1
Bi_2O_3	464.0	MgO	40.3	U_2O_3	524.4
B_2O_3	70.0	MnO	70.9	V_2O_3	150.0
CdO	128.4	Na_2O	62.0	ZnO	81.4
CaO	56.1	NiO	74.7	CO_2	44.0
Cr_2O_3	152.0	PbO	223.2	N_2O_5	108.0
CoO	75.0	SeO_2	111.2	Cl_2O_5	150.9
CaO	56.1	SiO_2	60.3	SO_3	80.0
FeO	71.8	SrO	103.6		

Ratio of oxide to salt	I.	II. Reciprocal of I.	Ratio of oxide to salt.	I.	II. Reciprocal of I.
B_2O_3 to $2B(OH)_3$	0.564	1.77	MgO to $MgCO_3$	0.478	2.09
$Na_2B_4O_710H_2O$	.366	2.73	MnO to MnO_2	.816	1.23
$Na_2B_4O_7$	.713	1.40	Na_2O to Na_2CO_3	.585	1.71
BaO to $BaCO_3$	.777	1.29	Na_2SO_4	.437	2.29
$BaSO_4$	.657	1.52	$2NaNO_3$	.365	2.74
CaO to $CaCO_3$	.560	1.78	$Na_2B_4O_710H_2O$	.162	6.11
CaF_2	.718	1.39	$Na_2B_4O_7$	.307	3.26
K_2O to K_2CO_3	.682	1.47	PbO to Pb_3O_4	.977	1.02
$K_2CO_32H_2O$	.541	1.85	PbO_2	.933	1.07
K_2SO_4	.541	1.85			
$2KNO_3$	.466	2.15			
$2KClO_3$	.384	2.61			

PRACTICAL APPLICATIONS.

As an illustration of the use of the foregoing diagrams the batches for several different types of optical glasses will now be deduced.

(*a*) *Ascertain the batch for an optical glass of refractive index,* $n_D = 1.649$ *and* $\nu = 33.7$.

By definition $\nu = (n_D - 1)/(n_F - n_C)$; accordingly the mean dispersion of this glass is $0.649/33.7 = 0.01925$. From figure 13 we find that a glass of these properties is a member of the flint series; we may therefore turn directly to figures 19 to 22 and 26 for the desired information; the batch may be read off directly from figure 26 or obtained less directly from figures 19 and 20. The refractive index curve of figure 20 shows that the percentage of lead oxide, PbO, contained in a glass of refractive index $n_D = 1.649$ is 52; from figure 19 in turn we find that the approximate composition of a flint glass containing 52 per cent PbO is SiO_2, 41; PbO, 52; and the alkalies (K_2O, or Na_2O, or m K_2O plus n Na_2O), 7. By means of the conversion factors listed in Table 7 we now convert the K_2O into a mixture of K_2CO_3 and KNO_3 such that the total amount of K_2CO_3 is three times that of KNO_3. A simple algebraic computation shows that this will be the case if 0.814, or, roughly, four-fifths of the total

amount of K_2O, is assigned to K_2CO_3 and the rest to KNO_3; the corresponding factor for Na_2O is 0.827. The batch then without allowance for volatilization is: Sand, 100 kiligrams or pounds; litharge (PbO), 126.8; potassium carbonate (anhydrous K_2CO_3), 20.4; potassium nitrate, 6.8. To correct for volatilization the lead oxide should be increased a little; as a first approximation subject to test and slight modification after a trial melt we may write: Sand, 100; litharge, 127; (or red lead Pb_3O_4, 130); potassium carbonate, 20.5; potassium nitrate, 6.8; and arsenious oxide (As_2O_3), 0.6.

The batch may also be read off directly from figure 29: Sand, 100; litharge, 127; K_2CO_3, 20; KNO_3, 7. In the batch diagram, as given, arsenious oxide is not included; it is, however, common practice among glassmakers to add from 0.2 to 1 kilogram As_2O_3 per 100 sand. Too much arsenious oxide especially in the flint glasses may cause the glass to turn milky on cooling; but a little is considered to aid in producing a colorless glass of high, brilliant luster.

In case the analysis of the raw materials shows the presence of an appreciable amount of water in any one of the substances, such as sand or potassium carbonate, proper correction for this should be made in computing the actual batch to be used.

It should be understood that these batch figures are of the correct order of magnitude only; that the nice adjustment of the batch depends on a number of factors which are best ascertained by actual trial; these factors include size and type of melting pot and of melting furnace, resistance of the pot to attack by the glass melt, furnace schedule, and treatment of the glass batch and melt. A departure of one or even two units in the third decimal place in the refractive index and of one or two tenths in the ν-value may be found on actual trial. A slight modification of the relative quantities of the batch substances suffices commonly to produce the desired results.

(*b*) *State the batch compositions of a glass of refractive index* $n_D = 1.517$ *and* $\nu = 64.3$; $n_F - n_C = 0.00804$.

The ν-value of this glass is so high that it is evidently a borosilicate crown. Reference to Table 4 of analyses indicates that the optical constants of glass No. 17 are closely similar to those desired. In general it may be stated that for a borosilicate glass of such high ν-value, the refringence is unusually high, whereas for a crown glass of this refractive index, the ν-value is too high. The presence of boron oxide in the glass raises its ν-value; but, if added in quantity, it lowers the refractive index; barium oxide, on the other hand, tends to raise both the refractive index and the ν-value. It is evident, therefore, that in order to attain the higher refractive index together with high ν-value, barium oxide should be substituted for the lime of the crown glasses and boron oxide should be present in appreciable quantities in order to approach the type of glass desired.

The ν-value of glass No. 17 is too low; in order to raise it slightly the relative amount of boron oxide should be increased somewhat. A batch computed on the basis of analysis 17 and modified in the manner indicated is the following: Sand, 100; $B(OH)_3$, 31; K_2CO_3, 31; Na_2CO_3, 21; KNO_3, 5.2; $BaCO_3$, 6; As_2O_3, 0.3.

In case a slightly lower ν-value, as 64.1 or 64.0, is desired, the amount of $B(OH)_3$ should be reduced to 30 or even 29. The interplay of boron oxide and barium oxide in optical glasses, as affecting their dispersion and refringence, is a most important factor for the glass-maker to realize.

(*c*) *State batch composition of a borosilicate crown of refractive index* $n_D = 1.511$, $\nu = 63.5$.

In this glass the refractive index is low and the ν-value high; there is no necessity, therefore, of substituting BaO for CaO. Analyses 9, 10, and 11 may serve as a basis from which to deduce a batch composition for this glass; thus an appropriate batch would be: Sand, 100; $B(OH)_3$, 12; Na_2CO_3, 22.6; K_2CO_3, 15; KNO_3, 9; $CaCO_3$, 4.5; As_2O_3, 0.4.

(*d*) *Select two glasses which in combination will produce a telescope objective nearly free from secondary spectrum.*

Secondary spectrum in a well-constructed telescope objective consisting of two glasses in combination results from the dissimilarity of dispersion in the two glasses. It can be readily proved that, other conditions being the same, the amount of secondary spectrum, for any spectrum interval, present in a doublet depends directly on the partial dispersion ratios of the two glasses and inversely on the difference between the ν-values.

The dispersion relations referred to in the foregoing pages enable us to select glasses which meet these requirements. They may in fact be selected directly by inspection of figure 15. As an illustration let it be required to select a suitable glass which may be used in combination with the zinc crown glass No. 26, of Table 4 of glass analyses. The optical constants of this glass are: $n_D = 1.5128$; $\nu = 57.3$; $n_F - n_C = 0.00894$; $n_D - n_{A'} = 0.00575$; $n_F - n_D = 0.00630$; $n_{G'} - n_F = 0.00508$. The ratio $(n_D - n_{A'})/(n_{G'} - n_F) = 1.132$. From figure 15 we find that glass No. 45, a dense barium crown, has approximately the same ratio between the two partial dispersions, namely, $(n_D - n_{A'})/(n_{G'} - n_F) = 1.127$. Its optical constants are: $n_D = 1.6098$; $\nu = 58.8$; $n_F - n_C = 0.01037$; $n_D - n_{A'} = 0.00665$; $n_F - n_D = 0.00730$; $n_{G'} - n_F = 0.00590$.[19] The partial dispersion ratios for the two glasses are:

No.	$\frac{n_D - n_{A'}}{n_F - n_C}$	$\frac{n_F - n_D}{n_F - n_C}$	$\frac{n_{G'} - n_F}{n_F - n_C}$
26.....	0.641	0.704	0.569
45.....	.642	.704	.569

From the analyses of these two glasses it is not a difficult matter to write down appropriate batches. Thus the batch for the zinc silicate crown, No. 26, is approximately: Sand, 100; zinc oxide, 17; sodium carbonate (Na_2CO_3), 34; and sodium nitrate ($NaNO_3$), 11.3, arsenious oxide (As_2O_3) 0.3. A suitable first trial batch for the glass No. 46 is sand, 100; boric acid ($B(OH)_3$), 69.5; alumina (Al_2O_3), 25.7; barium carbonate ($BaCO_3$), 199.5; arsenious oxide, 0.3. The function of the alumina in this batch is to lessen the tendency of the barium oxide to form crystallization nuclei of barium disilicate and also to improve the working qualities of the melt itself.[19]

From diagram 15 we note that a third glass, namely, the barium crown No. 27, has almost the same dispersion relations; its ratio $(n_D - n_A')/(n_G' - n_F)$ is 1.132. Its partial dispersion ratios are 0.640, 0.703, and 0.565 for the intervals D to A', F to D, and G' to F compared with the mean dispersion for the interval F to C. From analysis 27 a first trial batch composition may be computed by the methods outlined and found to be: Sand, 100; boric acid $B(OH)_3$, 9; zinc oxide, 8.4; barium carbonate, 41.7; sodium carbonate, 9; potassium carbonate, 18.5; potassium nitrate, 9.5; arsenious oxide, 0.5. The addition of more barium carbonate to this batch would raise the refractive index. As the amount of BaO is raised, that of the alkalies is lowered in order partly to reduce the corrosive action of the melt on the pot.

These examples suffice to indicate that the problem of batch compositions of optical glasses at the present time, until more data have been made available, is one of interpolation together with a certain amount of experience which enables the glassmaker to determine what the behavior of the melt will be under the conditions at his plant. In all cases it is advisable to prepare small melts, 5 to 50 kilograms in weight, to stir these properly, and to ascertain the optical constants of the finished glass. Good quality glass can not be produced by this procedure, and the conditions are distinctly different from those in the melt of a large charge of 500 to 1,000 kilograms; but the order of magnitude of the optical constants obtained is correct. It is also advisable to hold the small charge melt for a relatively long period of time at temperatures somewhat below the final stirring temperatures in order to ascertain the tendency of the melt to crystallize or to become milky and opalescent; the batch can then be modified accordingly.

It may be of interest to note that this part of the general problem of optical glass manufacture proved, during the war, to be one of

[19] The fact that the ν values of these two glasses are so nearly alike is unfavorable from a practical standpoint because under these conditions the power of the resulting combination is weak and steep curves are required to attain even a low power. Two glasses, for which the difference in ν values is less than 15.0, are not generally considered acceptable for achromatic doublets.

the least of our troubles and indicated the futility and uselessness of secrecy in this particular phase of optical glass manufacture. As a research problem, the general problem of optical glass manufacture in war time differs from ordinary research problems because the properties of the final product are definitely known and the task is to reproduce glasses of known characteristics rather than to develop new types of glasses. In the above paragraphs no consideration is given to the more fundamental problem of computing the optical constants of a glass from its chemical composition. The information at hand was not adequate for this purpose and our war-time interest was not concerned with this problem, which still awaits satisfactory solution.[20]

Among the batches for different types of optical glass which originated with the Geophysical Laboratory,[21]. those listed in Table 8 are typical:

TABLE 8.—*Batch compositions of optical glasses.*

	(A) Light crown. n_D=1.516 ν=60.0	(B) Boro-silicate crown. n_D=1.511 ν=64.1	(C) Boro-silicate crown. n_D=1.511 ν=63.4	(D) Boro-silicate crown. n_D=1.517 ν=64.3	(E) Barium crown. n_D=1.570 ν=57.0	(F) Barium crown. n_D=1.571 ν=56.7
Sand	100.0	100.0	100.0	100.0	100.0	100.0
BO_3H_3	.....	21.0	21.0	31.0	13.6	11.3
Al_2O_3	.....	.....	.....	.....	2.1	.....
As_2O_3	1.0	.4	.2	.3	.6	1.0
Pb_3O_4	.....	.....	.....	.....	.....	.....
ZnO	.....	.....	.....	.....	18.3	20.0
$CaCO_3$	20.0	5.0	4.0	.....	.....	.....
$BaCO_3$	4.7	.....	.....	6.0	75.3	76.7
K_2CO_3	10.0	15.6	15.0	15.0	5.2	22.0
KNO_3	12.4	14.0	3.0	5.2	11.3	5.0
Na_2CO_3	19.3	18.2	22.6	21.0	15.1	.....

	(G) Light flint. n_D=1.580 ν=41.1	(H) Light flint. n_D=1.570 ν=42.0	(I) Medium flint. n_D=1.605 ν=37.6	(J) Dense flint. n_D=1.640 ν=34.6	(K) Dense flint. n_D=1.649 ν=33.5	(L) Barium flint. n_D=1.619 ν=37.6
Sand	100.0	100.0	100.0	100.0	100.0	100.0
BO_3H_3	.....	.....	.....	.....	.....	.....
Al_2O_3	.....	.....	.....	.....	.....	.....
As_2O_3	.7	.1	.6	.7	.7	.6
Pb_3O_4	68.1	62.0	90.5	124.1	129.3	89.1
ZnO	.....	.....	.....	.....	.....	7.0
$CaCO_3$	.....	.....	.....	.....	.....	.....
$BaCO_3$	.....	.....	.....	.....	.....	19.0
K_2CO_3	9.4	14.2	10.3	5.3	20.0	21.3
KNO_3	8.8	8.5	7.8	10.3	6.7	9.6
Na_2CO_3	20.5	9.5	15.4	16.4	.....	.....

[20] The first five papers of a series of articles on "The development of various types of glasses" have recently been published by C. J. Peddle in the Jour. Soc. Glass Technology, 4, 3–107, 1920; see also "The optical properties of some lime-soda glasses," by J. R. Clark and W. E. S. Turner, Jour. Soc. Glass Technology, 4, 111–115, 1920.

[21] Batches *b*, *e*, *g*, *i*, *k*, *l* are taken from the article by C. N. Fenner, Jour. Am. Ceram. Soc., 2, 143, 1919.

TABLE 8.—*Batch compositions of optical glasses*—Continued.

PERCENTAGE EQUIVALENTS.

	(A) Light crown. $n_D=1.516$ $\nu=60.0$	(B) Boro-silicate crown. $n_D=1.511$ $\nu=64.1$	(C) Boro-silicate crown. $n_D=1.511$ $\nu=63.4$	(D) Boro-silicate crown. $n_D=1.517$ $\nu=64.3$	(E) Barium crown. $n_D=1.570$ $\nu=57.0$	(F) Barium crown. $n_D=1.571$ $\nu=56.7$
SiO_2	71.6	70.0	70.9	67.9	48.9	49.0
B_2O_3		8.3	8.4	11.9	3.8	3.1
Al_2O_3					1.0	
As_2O_3	.7	.3	.1	.2	.3	.5
PbO						
ZnO					8.9	9.8
CaO	8.0	1.9	1.6			
BaO	2.6			3.2	28.6	29.2
K_2O	9.0	12.0	8.2	8.5	4.3	8.4
Na_2O	8.1	7.4	10.8	8.3	4.3	

	(G) Light flint. $n_D=1.580$ $\nu=41.1$	(H) Light flint. $n_D=1.570$ $\nu=42.0$	(I) Medium flint. $n_D=1.605$ $\nu=37.6$	(J) Dense flint. $n_D=1.640$ $\nu=34.6$	(K) Dense flint. $n_D=1.649$ $\nu=33.5$	(L) Barium flint. $n_D=1.619$ $\nu=37.6$
SiO_2	52.7	55.6	47.9	41.7	41.3	43.8
B_2O_3						
Al_2O_3						
As_2O_3	.4		.3	.3	.3	.3
PbO	35.0	33.7	42.4	50.5	51.6	38.1
ZnO						3.1
CaO						
BaO						6.5
K_2O	5.5	7.5	5.1	3.5	6.8	8.3
Na_2O	6.3	3.1	4.3	4.0		

MAGNETIC SEPARATOR.

A number of experiments were made with a view to eliminate so far as possible the iron-bearing compounds which might be present in the raw batch materials, particularly the sand. For this purpose a magnetic separator of the Dings type proved to be the most efficient. By means of this separator the magnetic particles from the sand and from the cullet were extracted. It was found, however, that in the long run the amount of magnetic material obtained by this method was hardly sufficient to warrant the expense and trouble involved in the operation. In case, however, the raw materials are not of the highest quality a magnetic separator should render valuable service.

MIXING OF THE BATCH.

The raw materials which enter into the composition of the batch mixture must be thoroughly mixed before they are filled into the pot, in order that the composition before melting is practically uniform throughout. In smaller plants the mixing of the batch is done by hand after the manner of quartering in assay plants. The materials are weighed out accurately and passed through a sieve of four or six meshes per inch into a long, open wood box, large enough to hold the entire batch. (Fig. 30.) The batch is then thoroughly

worked over, back and forth, by shoveling the materials from one end of the box to the other; in this operation the effort is made to mix the materials by turning and spreading each shovelful. The workmen soon become skilled at this task, and analyses show that a highly uniform composition throughout the mass can be obtained by this method. It has, however, certain disadvantages. The shifting about of the powdered materials raises an appreciable amount of dust, which is breathed in by the workmen. The workmen are supposed to wear aspirators, but they are lax and may fail to regard this precaution; they inhale the dust of lead oxide, arsenic, and strong alkalies, and this in time seriously affects their health. This situation is somewhat improved by the use of strong ventilators

FIG. 30.—Mixing and sifting the materials for the raw batch by hand. (Photograph by J. Harper Snapp at the plant of the Spencer Lens Co.)

placed about the mixing boxes; such ventilators remove the fine dust from the room fairly well, but if the suction is too violent the lighter portions of the batch are apt to be carried away.

Mechanical mixers are in general use at large plants. (Fig. 31.) Experience has shown that these are efficient, the chief objection to them being that, if any metal parts, such as iron, are exposed these are abraded, and iron is thereby introduced into the batch. In the case of optical glass this may seriously affect the color of the glass. Of the mechanical devices the cube mixers lined with wood and equipped with paddles have proved satisfactory; also a conical mixer equipped with paddles. (Fig. 31.) Mixing by mechanical means is of course more rapid than by hand, but in the case of an optical glass plant the capacity is never so large that, were it not for

the danger to the men's health, mechanical mixers would probably not be used.

Cullet.—The quality of glass required for optical purposes is so high that the percentage of good glass finally obtained from each pot rarely exceeds 25 per cent. Part of this wastage results from the several operations through which the glass has to pass from the pot stage to that of final acceptance; but a considerable portion of the pot glass is rejected on first inspection because of striae, bubbles, shape and small size of fragments, and other defects. Rejects of pot glass are called "cullet," and are commonly remelted together with

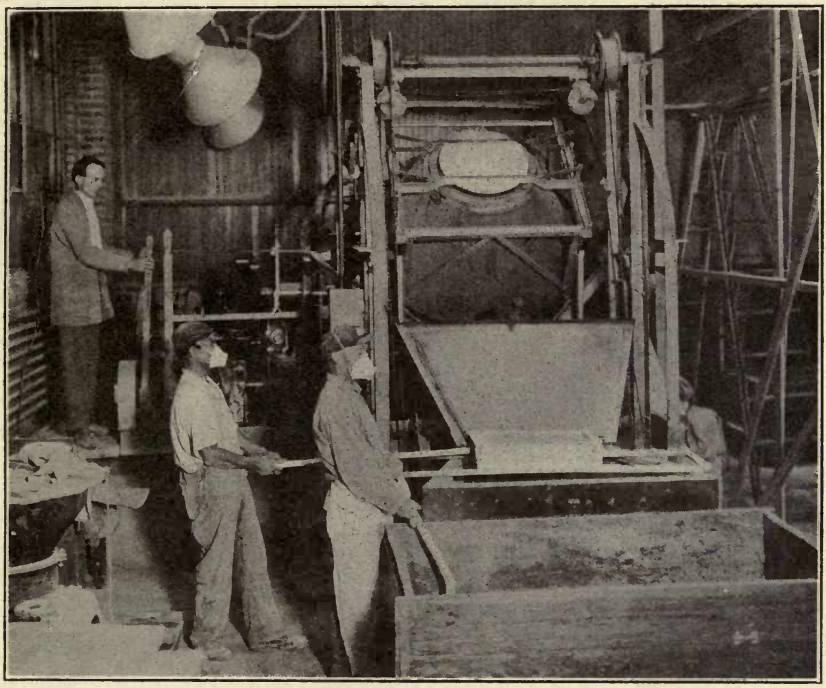

FIG. 31.—Mechanical batch-mixer. (Photograph by J. Harper Snapp at the plant of the Bausch & Lomb Optical Co.)

fresh batch. Two purposes are thereby served—valuable material is saved and the melting pot is protected in a measure from the active corrosive action set up on the melting down of the raw batch materials.

The amount of cullet which may be used is more or less indeterminate. Experience has shown that good results can be obtained from melts free from cullet; also from melts containing 50 per cent of cullet. Good practice is to use up the available cullet and not to allow it to accumulate. Cullet intended for a batch is broken up with a hammer or in a jaw crusher into pieces measuring not over 2

inches in diameter. In this form it is easy to mix with the batch materials and also to handle in a shovel or scoop. Iron may be introduced during this operation, and the cullet fragments should be passed over an electromagnet before mixing with the batch materials. In the handling of cullet the most scrupulous care must be taken to keep the cullet from a particular pot of glass separate from all others. The object in all cases is to obtain optical glass of predetermined optical constants, and the admixture of any cullet of abnormal optical constants has a pronounced effect on the optical constants of the final product. Furthermore, cullet, after having been once through the melting process, is commonly richer in iron and other impurities than the raw batch materials. Cullet which is strongly colored should therefore be used only in limited quantities. In case the optical constants of available collet are slightly different from those of the glass desired it is the task of the manager so to adjust his raw batch composition that the resultant glass will have the correct values. If large quantities of cullet are used, it is considered to be good practice to increase relatively the amount of nitrates in the batch in order to produce an actively oxidizing melt. In no case should cullet containing stones or fragments of pot wall be used.

FURNACE OPERATIONS.

We come now to the most spectacular and to the novice the most interesting period of the glassmaking process. The batch is moved from the batch room to the furnace hall, where it is to pass through a fiery furnace and there to be transformed into glass. The glassmaking process consists not of a single operation, but of a series of operations which are carried out one after the other and for which a definite schedule is commonly arranged. These operations include: (*a*) Preheating, in a pot arch, of the pot in which glass is to be melted; (*b*) transference of the pot from the pot arch to the melting furnace and setting of pot on even keel in the furnace; (*c*) baking or burning the pot at a very high temperature; (*d*) glazing of the pot; (*e*) filling in the batch; (*f*) melting and fining; (*d*) skimming and stirring; (*h*) cooling of melt in furnace; (*i*) removal of pot from furnace; (*j*) cooling of pot to room temperature. These steps will be considered in the order named.

Preheating of the pot in the pot arch.—To be effective the furnace hall of the optical glass plant requires not only melting furnaces in which to melt the batch but also a number of pot arches in which to preheat the melting pots. The pots, as they are received from the pot-maker, are thoroughly well dried and free from cracks. Although massive in appearance and several inches thick, they are in fact very fragile and must be handled with the utmost care as they

are in reality built-up clay masses which, if jarred severely, may crack and fall apart.

The clay of the crucible contains even in the dry state a large amount of water in chemical combination as well as adsorbed water; this must escape during the heating of the crucible. It is the task of the glass maker to heat his crucible so slowly and so uniformly that during the operation it does not crack. The heating is commonly done in a simple type of gas-heated furnace, equipped with a short stack, in which gas flames mount over the breast wall, pass along the arch or crown and are drawn out through openings in the floor of the furnace. A pot arch of this type is not difficult to regulate, but it requires constant care to keep it properly regulated. If the gas flames play directly on the green pot a crack is certain to develop along the path of the flame.

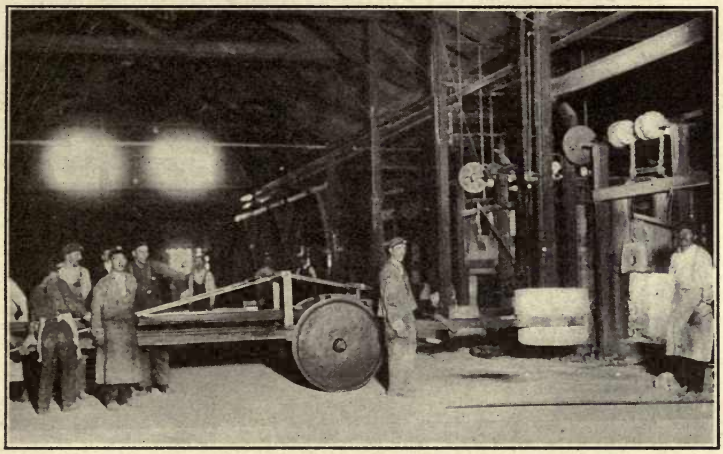

FIG. 32.—Preheated pot in process of transfer from pot arch to melting furnace. Furnace door is raised and furnace siege (floor) has been made ready to receive pot. Pot is transferred by a "pot wagon." (Photograph by J. Harper Snapp at the plant of the Bausch & Lomb Optical Co.)

The melting pot is placed on three firebrick supports 6 or 8 inches off the ground in the pot arch; the arch is sealed and the heat turned on slowly. The period of slow preheating depends on the size and kind of crucible; but ordinarily three to five days is about right; by this time a temperature of 800° to 1,050° C. (1,475° to 1,900° F.) has been reached and the hot pot may be transferred to the melting furnace which is heated to about the same temperature. The pots are transferred by means of a pot wagon, which may be described as a huge pair of tongs (mounted on wheels and with adjustable counterweights) which grasp the pot beneath the outer flange of the pot. (Fig. 32.) Half a dozen men can handle without difficulty a 36-inch pot even when filled with glass and weighing 1,500 pounds.

Setting of the pot.—During the period of intense heat developed in the melting furnace its floor or "siege" becomes somewhat soft, the

pot of molten glass sticks to it and on removal has to be pried up and loosened from it. This operation leaves the siege uneven. Before introducing the preheated, empty pot the glassmaker accordingly uses long iron rods and pushers to level the siege. He scrapes off protruding high spots as well as possible and then fills in the cavities with fresh sand and spreads a final thin layer of sand over the pot area in order that the pot may rest on a firm, level foundation and not be subjected to unnecessary strains. Care should be taken not use too much fresh sand in this operation, otherwise the siege becomes too high in the course of time.

The pot is set on the level siege, the furnace door (tuille) is lowered and sealed, and the fire is turned on.

Baking of the pot.—In the course of several hours a furnace temperature of 1,400° to 1,500° C. is attained; the empty pot is baked at a temperature of 1,425° to 1,450° C., depending on the kind of pot, generally for an hour or more to allow the clays to sinter together and even locally to show incipient melting, so that the texture of the pot walls becomes dense and is then not readily attacked by the molten glass. The pot is purposely superheated above the fining temperature of the glass, in order to render its inner walls dense and chemically resistant. The duration of the burning differs with the kind of pot employed, but it should always be sufficiently long to insure proper quality of walls. The burning may be done in a pot arch providing a sufficiently high temperature can be reached in the arch; in this case the pot, after burning, is transferred to the melting furnace, thus shortening the glass-melting period.

Glazing of the pot.—After thorough baking of the pot the furnace temperature may be lowered to the fining temperature of the glass or even slightly lower, to 1,325° C. (2,300° to 2,400 F.). Charges of 40 to 50 pounds of cullet are now filled into the pot at intervals of half an hour by means of a long-handled scoop or ladle; more cullet may be used if desired. In filling in the cullet from his scoop, the glassmaker endeavors to spread the material around the inside upper walls of the pot, whence it flows to the bottom, which it should cover to a depth of at least an inch. The function of the cullet glaze is to protect the walls of the pot from the batch. If the glazing is done at a very high temperature there seems to be a tendency for the thin molten glass to enter into the pot walls and leave them dry and unprotected. The glazing period may extend over one to three hours, depending on the amount of cullet used and on the furnace time-schedule. The furnace has now been held for several hours at a high temperature; during this period its walls and regenerative chambers have been heated thoroughly and a reserve amount of heat has been stored up to aid in the rapid melting down of the cold batch and thus to obtain a satisfactory fining period

Filling in the batch.—After the glazing of the pot, the batch is filled in at intervals. This operation should proceed in such a manner that the batch is introduced in quantities sufficiently small that they do not seriously cool down the melt in the pot and yet large enough to insure an economical use of fuel and of time. (Fig. 24.) With each fill of the batch and consequent opening of the furnace port, there is a perceptible cooling down of the furnace; with the introduction of each ladle of the batch there is furthermore an appreciable amount of the batch lost, which rises as a cloud of dust, enters into the furnace chamber, and is carried away by the gases; the dust settles in part on the walls and arch of the furnace and shortens its life appreciably. During the filling-in period the temperature of the furnace should be kept fairly high. If the temperature is held too low, the reactions within the melt proceed slowly and uneconomically; if too high, the reactions proceed too violently and the pot may boil over and be seriously attacked by the chemicals. Each successive fill of batch-mixture is made before the preceding fill has been completely dissolved and while undissolved grains of sand are still present in the melt. Experience has shown that the filling may be done at high temperatures without serious attack of the body walls. It is the task of the furnace operator to hold the temperature of the furnace sufficiently high that the melting down proceeds fairly rapidly without serious danger of boiling over and without serious attack on the walls of the crucible. In short, the filling-in should not be done in such large quantities that the pot is appreciably cooled; nor at too frequent intervals, nor in too small quantities; otherwise there is serious loss by volatilization and escape of dust. As the filling-in proceeds, the temperature of the furnace should be raised to the fining temperature which ranges from 1,375° to 1,425° C. for the ordinary kinds of optical glass. The pot is filled finally with metal to within an inch of the top.

Melting and fining.—There are certain features of the glass-melting process which have not yet been definitely established and which can only be approximately determined because of the number of variables involved. Raw materials of high purity are essential; freedom from iron is necessary because it is the chief coloring agent. The danger of iron coloration from pot solution can be reduced by using pots of high chemical resistance and low iron content, by a thorough baking of the crucible at a temperature considerably above the fining temperature of the glass, and by shortening the glass-melting period as much as possible. Experience has shown also that the iron in the ferrous-ferric state produces a maximum amount of coloration with a given percentage of iron; that iron in the ferric state produces relatively much less coloration. It is essential, therefore, that care be taken to run the furnace with an appreciable excess of hot air;

if the furnace construction is good the atmosphere above the batch is oxidizing and long lazy reducing flames do not sweep across the top of the pot and tend to reduce the ferric state of the iron. In the regenerative type of furnace a reducing atmosphere is avoided by first shutting off the gas on one side of the furnace, opening the butterfly, and then waiting for half a minute before turning on the gas on the opposite side of the furnace. This plan enables the furnace to get into proper balance and draft, and eliminates the presence of black sooty flames every time the direction of gas flow is reversed (10 or 20 minute intervals). Experience with furnaces indicates that the regulation of the temperature of the glass-melting furnaces is one of the most important factors in the manufacture of optical glass; this applies not only to preheating and baking of the empty pots, but also to the filling-in and the glass-melting temperatures.

The filling in of the batch and the complete melting and solution of the batch components is accompanied by an evolution of the volatile components of the batch; the final product is a solution of silicates free from bubbles. Experience has shown that agitation or vigorous stirring of the melt during, and especially toward the end of the filling-in period accelerates the solution and melting down of the batch and tends furthermore to reduce the differences in concentration in different parts of the melt. In particular it prevents the heavy lead oxide components of the batch from sinking to the bottom and thus forming a heavy layer which later is difficult to eliminate. Moreover, the stirring of the melt during the period of intense chemical reaction tends to favor the escape of any bubbles which may be formed. The stirring should not be so violent that the foam which forms on on the surface of the glass melt is stirred into the glass mass. Stirring at this period decreases the time of melting and shields the pot from attack by the solutions and cuts down the amount of gas used. As a result of the intensive study of these factors Dr. G. W. Morey,[22] of the Geophysical Laboratory, was able to shorten the melting period from 36 hours to 24 hours.

At the end of the filling-in period, the glass is fairly well melted, but the chemical reactions, which take place and which mean the replacement of carbonates and nitrates by silicates and borates (if boron be present) and the driving off of the volatile gases, require some hours for completion; during most of this period the molten glass is filled with small bubbles and the escaping gases and chemical reactions tend to keep the temperature of the melt down. Toward the end of the process, the volatile gases have for the most part escaped. The temperature of the melt may now rise. The evolution of

[22] G. W. Morey, An improved method of optical glass manufacture, Jour. Am. Ceram. Soc., 2, 146-150, 1919.

gas becomes more pronounced, the melt enters the stage of the "open boil," and then passes into the "fine or plane" stage at which it is relatively free from bubbles and seeds.

In the glassmaking industry the fining of the glass melt is a most important factor. The fining is evidently a stage attained by the melt in which the saturation limit for the gases ($CO_2$and N_2O_5) is relatively low and presumably becomes progressively lower as the carbonates and nitrates are eliminated from the melt. There is some evidence that the batch containing only nitrates and no carbonates fines at a lower temperature than the nitrate-carbonate batch; there is also evidence that at high temperatures arsenic pentoxide dissociates into oxygen and arsenic trioxide and causes an evolution of gas which tends to sweep the glass metal clear of small seeds toward the end of the fining period. Because of its importance to the whole glass manufacturing industry a careful study of the gas evolution-time-temperature relations in different glass batch types should be undertaken; preliminary investigations along these lines have been undertaken by Dr. E. G. Zies, of the Geophysical Laboratory. The data obtained by these studies should give a clearer insight into the glass-melting process than has heretofore been possible and will enable glassmakers to establish scientific control over their melts. The problem is fundamental in character. The study of the chemical reactions at high temperatures which take place on the conversion of the carbonate-nitrate solutions into a solution of silicates is essentially that of the glassmaking process, and the more we know of these reactions and their rates, the better can they be controlled.

The optimum temperatures for fining the glass are different for different glass types. In general the crown glasses (light crown, borosilicate crown) fine well at 1,400° C. or a little higher. Medium flint melts, on the other hand, are less viscous and fine well at 1,370° C. In case there is danger of milkiness, because of the presence of small amounts of chlorides or sulphates, or too much arsenic or other opalescence-producing compound, the melt should be fined at a higher temperature, 1,425° C. or still higher, if the pot will stand it. At high temperatures the pot may become fairly soft and be attacked by the metal, and stones or leakage may result; furthermore, because of increased volatilization, the optical constants of the melt change rapidly.

The ease with which molten glass rids itself of bubbles depends somewhat on the type of glass. The flint glasses are relatively liquid and commonly fine readily. The crown glasses are in general more viscous and may cause trouble during the fining stage. To facilitate and to expedite the fining of the glass, "blocking" of the melt is frequently resorted to; this process consists in introducing into the melt a small amount of some volatile substance, such as water, which

on escaping forms large bubbles and sets the melt in violent agitation. The details of this process are described below in the section on stirring.

At different periods during the melting and fining stages of the glass, proofs or dips are taken to ascertain the condition of the metal. For this purpose an iron rod flattened at the end, with a shallow cup attached to the bent end of the rod, is inserted into the metal and a sample of molten glass is ladled out; or a small quantity of glass is gathered on the end of a small iron pipe and blown into a spherical flask. The operation is done as quickly as possible; the rod with its dip of attached glass is withdrawn and examined during cooling. In the case of proofs the base of the cup is cooled in a pail of water; the hemispherical proof is then removed and placed on top of the melting furnace, where it cools down slowly.

Skimming.—Toward the end of the fining period bubbles of fair size escape freely and the stage of "open boil" begins; with the close of this period the melt is reasonably free from seeds and bubbles and is said to be "fine" or "plane." During the fining process scum, stones, and other materials which are specifically lighter than the metal rise to the top and can be seen floating on the surface; these are removed by "skimming." A long iron rod with a cross plate attached to the end is passed over the surface of the metal and the froth is skimmed off. Care is taken in this operation not to submerge any of the floating islands of scum because they reappear only slowly; also not to remove any more of the good glass than is necessary because of the changes in optical constants of the glass which may result therefrom.

Stirring.—Ordinary types of glass consist chiefly of silicates in solution; geological and experimental evidence proves that silicates, such as are found in glass and in igneous rocks, are miscible in all proportions. From the layers which are sometimes observed in optical glass melts, especially in the heavy flints, one might infer that limited miscibility between certain phases exists; but it is easy to prove that the layers are the result of gravitative differentiation, the heavy, lower-melting lead oxide and other components of the batch settling to the bottom, the light sand particles rising to the surface. Such stratification in layers of different density is not an uncommon thing in glass melts and is overcome by stirring and by blocking. Once the melt has been rendered thoroughly homogeneous slight differences in composition may still be introduced as a result of volatilization from the surface of the melt and solution of the pot walls along the sides and bottom. The chief purpose of stirring is to render the melt homogeneous.

Stirring was first introduced by P. L. Guinand, a Swiss maker of glass, who used a clay stirring rod operated by hand. Guinand pro-

duced glass of good quality, some of which was used by Fraunhofer in astronomical telescopes. Hand stirring (fig. 33) is still employed at many factories during the early part of the melting period for the purpose of thoroughly mixing the melt so that great differences in composition do not exist; the stirring begins while the melt is still active and undissolved sand grains are still present. Stirring at this stage of the process accelerates the chemical reactions within the melt and aids greatly in the attainment of homogeneity. Hand stirring of this kind is best done intermittently in order not to cool down the molten glass appreciably and also to allow bubbles to escape.

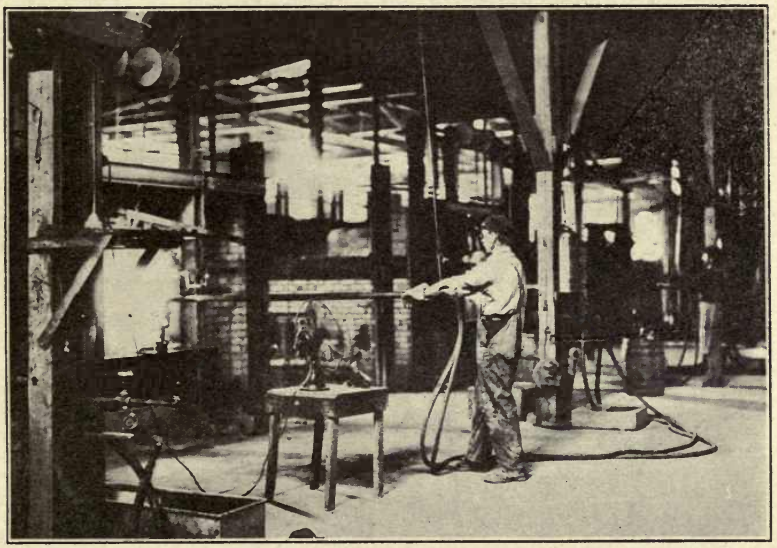

FIG. 33.—Stirring an optical glass melt by hand. (Photograph by J. Harper Snapp at the plant of the Bausch & Lomb Optical Co.)

Following Guinand's practice, the clay stirring tube or thimble is first carefully heated to a bright red in a small gas furnace and then placed on the breast wall of the melting furnace where it attains a white heat; from here it is conveyed to the edge of the melting pot, inserted slowly into the melt and then withdrawn and allowed to remain for another hour on the edge of the crucible with its closed end floating on the molten glass. This treatment allows the glass to penetrate into the clay mixture and to drive out gases which would otherwise escape into the melt and be difficult to eliminate. The clay tube is now attached to the end of the water-cooled rod, and stirring by hand or by machine may begin. The clay stirring tubes should be at least 3 inches thick at the bottom and 4½ inches at the top with a collar 1 inch thick to give strength to the end of the tube into which the elbow end of the water-cooled stirring rod passes; also

to furnish a flange with which to support the tube when the stirring rod is removed. The tube should be about as long as the pot is deep. The tubes are commonly made at the plant from the material of raw, broken pots. (Fig. 34.) The end of the water-cooled, iron-pipe stirring rod is preferably a square block of iron about 4 inches long and 1 inch thick, set at right angles to the rod; it fits fairly snugly into the square hole at the top of the fire-clay stirring tube and holds it in position during the stirring operation.

If hand stirring is used, the water-cooled stirring rod passes over a small grooved iron wheel, mounted on a pivot directly in front of the small opening in the furnace door. (Fig. 33.) To relieve the workman of supporting the heavy rod during the stirring operation, it is counterbalanced by weights suspended from pulleys which con-

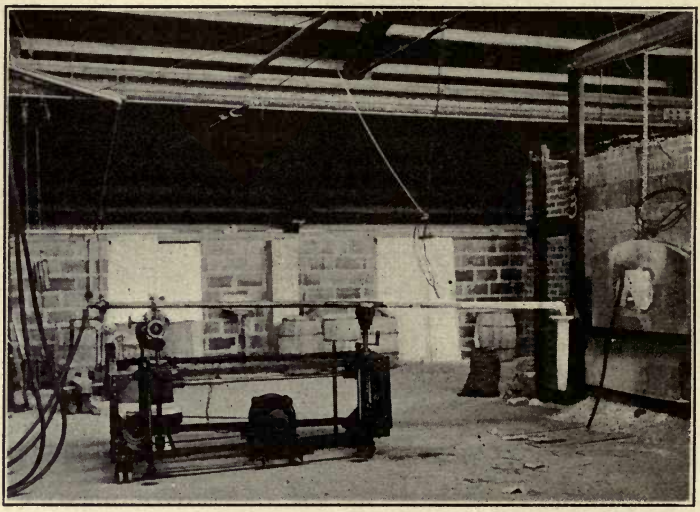

FIG. 34.—Clay stirring-rod attached to water-cooled stirring rod mounted on a stirring machine. (Photograph by J. Harper Snapp at the plant of the Spencer Lens Co.)

nect to its cold end; at this end a crossbar, preferably of wood, is attached and with it the rod is held and guided by the workman. Skill and practice are required to stir well by hand. There is danger at first of scraping the sides and bottom of the pot and of disengaging the clay tube, but with practice the motions become routine and workmen find no difficulty in stirring continuously during a 20-minute shift. During actual stirring the eyes of the workman are shielded by proper glasses to cut down the intensity of the light and heat radiated from the furnace.

Hand stirring is satisfactory for the early stirring operations, but the mechanical stirrer is superior for the long-continued stirring which follows. The mechanical stirrer is an electrically driven device mounted on a heavy framework which runs on wheels and can be

moved from one furnace to another. (Fig. 34.) Different mechanical means are employed to impart to the stirring tube the desired motions. A rotating metal plate can be used, to which the cold end of the stirrer is attached; and by an automatic screw feed this end can be made to describe circles of continuously varying radii if desired; the middle of the tube is pivoted on a metal pin which slides in a groove that can be inclined at different angles, thus imparting the desired degree of up-and-down movement to the stirring tube. A maximum up-and-down stroke of the stirring tube of 4 to 6 inches is about right. With this arrangement the curves described by the stirrer are approximately circles [23] combined with the up-and-down stroke. The stirring machine is adjusted to proper height of the stirrer by means of small jackscrews permanently attached to the framework. Similar motions of the stirrer can be accomplished by means of systems of gearing (planetary) and have proved satisfactory in practice. The curves described by these systems, especially if the axis, on which the rod is pivoted, is fixed, may depart in shape considerably from a circle. The requirements to be met by the mechanical stirrer are: Ability to impart to the stirrer approximately circular motions of different diameters; at the same time an up-and-down movement if possible; variable speeds varying from 30 down to 4 or 5 revolutions per minute (speed preferably continuously variable or if by steps, by at least four steps); stirring rod easily and quickly removable; ease and certainty of manipulation. In all mechanical stirring the stirring tube should never approach nearer than 2 inches to the sides or bottom of the pot.

The significance of the stirring process is best realized by analogy. In the case of sugar dissolving in hot water or tea the obvious method to expedite the rate of solution and to render the solution homogeneous is to stir it vigorously with a spoon. Similarly, fine or heavy striæ can be absorbed and the glass rendered homogeneous by effective stirring; but this stirring must be done in such a way that the different parts of the melt are thoroughly mixed and at sufficiently high temperatures that the rate at which diffusion acts to eliminate differences in concentration is sufficiently rapid to enable the glass to become homogeneous within a reasonable period of time. The higher the temperature the thinner the metal and the more rapidly are the differences of composition eliminated by diffusion. The need for an up-and-down and an in-and-out motion with a stirring rod of sufficient size to be effective is evident. A homogeneous solution of silicates can only be obtained by proper stirring methods applied at proper temperatures. The solutions are not individual units, such as crystal compounds of definite compositions, but they are solutions of silicates mutually soluble which dissolve the one in the other and finally

[23] Williamson and Adams, Jour. Am. Ceram. Soc., 3, 671–677, 1920.

merge completely to produce a homogeneous mixture. These principles are stated somewhat in detail because they are fundamental to the attainment of good optical glass. This treatment of optical glass is different from that of any other kind of glass, such as plate glass, and may therefore not appear to be important to the skilled maker of plate or window glass whose interest centers chiefly in seeds and heavy striæ, but not in fine striæ which are almost imperceptible to the unaided eye.

An instructive experiment to illustrate the formation of striæ and the effect of proper stirring on the elimination of striæ is to mix, in a beaker glass, glycerin and water, or glycerin and alcohol, or syrup, honey, or molasses and water; stirring rods of different shapes and sizes may be used to ascertain the effects of the different possible methods of stirring. During the first part of the mixing process the more viscous liquid (glycerin or syrup) forms a series of veins, strings, ribbons, which disturb the even course of the light rays through the solution and render it semitransparent. As the stirring continues the heavy cords and threads decrease in distinctness and sharpness and the solution appears to be filled with fine lines. After further stirring the solution becomes clearer and finally attains a state of complete mixing; it is practically homogeneous. These experiments aid the observer in visualizing the stirring process and impress him not only with the significance of striæ and their elimination, but also with the relatively long period of time required to render even a relatively thin solution, such as glycerin and water, homogeneous; he realizes at once the importance of the thorough and long-continued stirring of optical glass at high temperatures in order to attain homogeneity.

In the early stages of the final melting process of optical glass pronounced differences in composition exist in the glass melt; diffusion acts to diminish these differences in concentration. The rate at which this is accomplished depends on the concentration differences from point to point in the melt; the more numerous and the greater these differences are between adjacent points, the more rapid is the transfer of material by diffusion and the sooner is homogeneity attained. Elements of different composition are spread out and brought into direct contact by stirring. Although at high temperatures the pot walls are dissolved more rapidly, yet unless the stirring is carried on at a high temperature it is ineffective, and fine striæ are introduced which are not completely digested by the metal.

The function of the first part of the stirring process which takes place while solution within the melt is still active is to mix the melt thoroughly. The stirring is done rapidly and the melt is vigorously agitated. This kind of stirring should be maintained until all elements in the batch have been completely dissolved and the volatile

onents have escaped. It is not necessary, however, that the ring be carried on continuously during this period; in fact, it is ter to stir the melt intermittently, because during this stirring iod the temperature of the furnace necessarily falls and the melt cooled somewhat. Thus by stirring for 15 minutes and then sing up the furnace and allowing it to attain a high tempera- ire, the chemical reactions take place more rapidly and there is less chance for great differences in concentration to be set up. Such stirring is best done by hand and an effort is made to stir up-and-down and in-and-out with a spiral motion. This part of the process nixes the melt thoroughly and aids bubbles to escape. The stirring should not be done so rapidly that escaping bubbles are carried down nto the melt. Toward the end of this process the characteristic tage of the reaction known as the "boil" of the molten glass begins and stirring by machine may now commence.

As an aid to hand stirring, blocking may be used; this mode of treat- nent aids also in the finishing of the melt. Blocking consists essentially in introducing into the melt a highly volatile substance, such as water, or arsenious oxide, or ammonium nitrate, which produces a sudden evolution of gas; this gas, on escaping through the melt, agitates it violently and tends not only to mix the melt, but also to sweep out any fine bubbles which may be held in it. The method of blocking has been used for many years in the plate and window glass industry and derives its name from the fact that blocks of wood soaked in water and held by a proper clamp are commonly thrust down into the melt; the intense heat causes a violent evolution of steam from the water, which produces the desired effect. Lumps of arsenious oxide answer the same purpose; also sticks of ammonium nitrate. An iron rod is used almost invariably in this connection and inevitably introduces a certain amount of iron into the melt. For optical glass this would be serious if the amount were appreciable, and care should be taken to employ clean iron rods free from scale. The method of blocking can not entirely replace hand stirring because the whole blocking action lasts for an exceedingly short time; but as an aid in fining the glass and in bringing about an open boil, blocking may be advantageous. The blocking is most effective if introduced at the beginning of the "open boil" stage of the melt. The injection of blocking material should be repeated several times in rapid succession, to be followed after an interval of 10 to 20 minutes by a second series of similar injections.

The glass is now fairly homogeneous and the task is to attain still greater homogeneity. This is best attained by mechanical stirring at temperatures slightly below the fining temperatures. During the melting process the glass is in a constant state of change. Volatilization of certain components of the melt proceeds at an appreciable rate from the time the batch enters the pot until after the pot has

been removed from the furnace; the walls of the pot are moreover attacked and solution of these walls takes place at a rate dependent on the quality of the pot. The changes in composition which arise from these two sources are restricted, chiefly to the margins of the melt, namely, the bottom, the sides, and the top. In all cases these changes tend toward an increase in the percentage of silica in the melt. Any factor therefore which produces a movement of the margins of the melt toward the center necessarily introduces into the melt streaks of different composition and hence of different optical properties. The factors involved in such transfer of materials are primarily mechanical movement and thermal convection currents set up as a result of differences in temperature between different parts of the metal; in the case of pot solution the lighter, more siliceous material from the pot tends to rise, thus setting up a current and allowing fresh melt to continue the attack on the walls. It is important that the temperature of the furnace be kept uniform, and that the stirring be done in such a manner that the marginal parts of the melt are disturbed as little as possible. In the case of pots which are chemically resistant, the danger of trouble from the walls of the pot is relatively slight and glass of good quality should extend to the margin of the pot. The stirring rod during mechanical stirring should not approach nearer than 2 inches to the sides or bottom of the pot, the object being to insure homogeneity in the central part of the glass mass and to shield this by leaving an undisturbed shell of molten glass between it and the pot walls. At the beginning of the period of steady mechanical stirring the rate of stirring should be fairly rapid (25 to 30 strokes per minute); there is, however, no special reason for a pronounced up-and-down movement at this stage, because by this time the differences in concentration between different parts of the melt are small and the function of the stirring is simply to eliminate these small differences and to obtain a melt uniform in composition throughout. Machine stirring at fairly high temperatures is continued for some hours and a high degree of homogeneity is attained thereby in the melt.

Were it now possible to have the molten glass acquire instantaneously room temperature in a well-annealed state, much of the glassmaker's troubles would be eliminated; but this is not the case, and the furnace operator endeavors during the cooling-down period to retain the homogeneity which the metal has acquired. This period is critical, and much glass may be lost in this operation unless extreme care be taken.

The gas is turned off and furnace and melt are allowed to cool slowly. Stirring is continued, but at a decreased rate and with shorter stroke, and the vertical motion is eliminated. The function of the stirring from now on is defensive only and seeks to efface the

inhomogeneities introduced by convection currents into the melt from the walls and bottom of the pot and from the surface of the melt at which selective volatilization is ever active. These sources of inhomogeneity do not produce great changes in the total composition of the melt, but, if allowed to be carried by convection currents through the melt, they leave a trail of very slightly different composition and this means striæ in the final product. When we consider that the refractive index of a heavy stria or cord differs from that of the inclosing glass by only one or two units in the third decimal place, we realize how slight the differences in chemical composition actually are and how essential it is to aid diffusion in smoothing out these minute differences by persistent stirring.

The rate at which to stir the molten glass during the cooling-down period is a matter to be learned by experience. It is desirable at all times to stir it as rapidly as possible but with certain limitations. As the melt cools the glass becomes stiffer, and the stirrer tends to carry before it a wave of glass which becomes higher and more pronounced the more viscous the glass and the faster the stirrer travels through it. The stirring should not be so rapid that part of this wave is at any time infolded into the wall because bubbles and the lower refracting surface film are thereby introduced; the stroke should, moreover, be so slow that the glass at the margin of the pot is left undisturbed.

During this part of the process there is little chance for the bottom of the pot to cool off, and it tends to function as a heating plate and to set up convection currents within the melt. The effect could be eliminated, if there were some easy method available for raising the pot and setting it on fire-clay supports at this stage, but no satisfactory method for accomplishing this is known to the writer. It is well to keep the door (tuille) of the furnace raised slightly during this period so that through the opening, several inches high, along the bottom, cool air can enter and cool the base of the pot. In case of necessity a cold air blast may be directed against the base of the pot; this has been tried, but the results attained do not seem to warrant the extra trouble involved.

Stirring of a cooling-glass melt can not be continued indefinitely because the glass becomes so stiff that further movement is impossible. It is the task of the glassworker to determine when stirring shall cease and the pot be removed from the furnace. It is desirable to continue the stirring as long as possible in order to reduce to a minimum the danger from convection currents, which move very slowly in an extremely viscous melt; on the other hand, if the stirring is continued to too low a temperature, the glass becomes so stiff that the mass adhering to the stirring tube grows in size and sweeps far

out into the marginal shell of the metal, thus introducing striæ which the steady stirring seeks to avoid.

The temperatures at which different types of glass should be removed from the furnace range from 1,150° C. in certain barium crown glasses to 900° C. in dense flint glasses. Having once ascertained the best temperature for removal of a given type of glass in a given size of pot, the glassmaker endeavers to remove other pots of the same type at the same temperature. To accomplish this, he plots on a chart the temperature readings, and by extrapolation of the time-temperature curve determines the exact time for removal of the pot. This question of pot removal has been closely studied by Dr. C. N. Fenner;[24] the procedure which he adopted for two of his glass types is illustrated in figure 35. A record of the several operations in his treatment of the two glasses is also reproduced from his article.

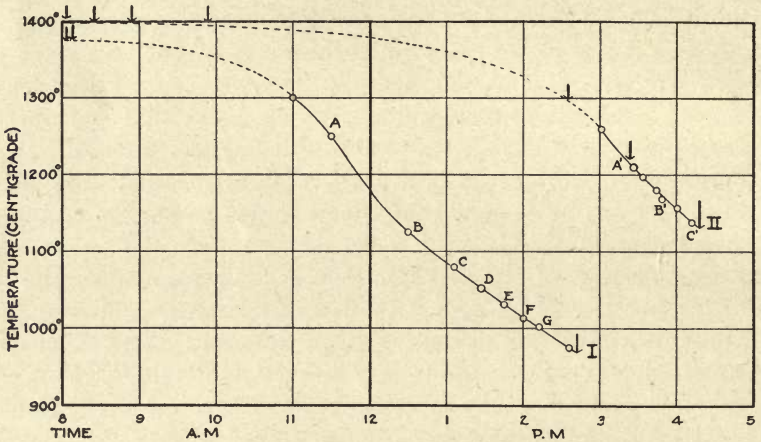

FIG. 35.—Time-temperature curves illustrating the procedure followed by C. N. Fenner in furnace operation during the stirring operations of two different types of glass, namely, medium flint (Curve I) and ordinary crown (Curve II).

EXAMPLES OF PROCEDURE IN STIRRING (AFTER C. N. FENNER).

MEDIUM FLINT (n_D=1.605, ν=37.6).

Pot 25 inches inside diameter at bottom, 27 inches deep. 8.03 a. m., started stirring machine at 13 revolutions per minute. Radius of stirring circle 6⅛ inches; vertical motion 4¼ inches. (NOTE.—A stirring circle of greater radius would have been preferable.)

8.07 a. m. Changes speed to 18 revolutions per minute.

11.00 a. m. (Temperature 1,300° C.) Shut off gas and air and lowered stack damper.

11.30 a. m. (Temperature 1,250° C.) Took off vertical motion (A fig. 35).

12.30 p. m. (Temperature 1,125° C.) Reduced radius of stirring circle to 5⅛ inches. (NOTE.—Might have been kept a little larger (B fig. 35).

1.05 p. m. (Temperature 1,080° C.) Speed reduced to 13 revolutions per minute. (C fig. 35).

[24] The technique of optical glass melting, Jour. Am. Ceram. Soc., 2, 133–138, 1919.

1.27 p. m. Radius of stirring circle reduced to 4 inches (D fig. 35).
1.45 p. m. (Temperature 1,030° C.) Radius of stirring circle reduced to 3¼ inches (E fig. 35).
2.01 p. m. (Temperature 1,013° C.) Radius of stirring circle reduced slightly (F fig. 35).
2.13 p. m. (Temperature 1,003° C.) Radius of stirring circle reduced to 1½ inches (G fig. 35).
2.35 p. m. (Temperature 975° C.) Stirring stopped.
2.40 p. m. Pot out. (NOTE.—A temperature of 950° C would have been preferable for this type of glass.

LIGHT CROWN (n_D=1.516 ν=60).

Pot 25 inches inside diameter at bottom, 27 inches deep.
8.03 a. m. Stirring machine started at 13 revolutions per minute. No vertical motion. Radius of stirring circle 6½ inches.
8.25 a. m. Changed speed to 18 revolutions per minute.
8.55 a. m. Changed speed to 13 revolutions per minute.
9.50 a. m. Reduced radius of stirring circle to about 5 inches. (NOTE.—A proof taken just before this had shown numerous bubbles; speed of travel was reduced to avoid danger of stirring air into the metal.)
2.35 p. m. Shut off gas, air, etc.
3.02 p. m. Temperature 1,259° C.
3.25 p. m. Radius of stirring circle reduced to 4 inches (A′ fig. 35).
3.35 p. m. Temperature 1,197° C.
3.45 p. m. Temperature 1,182° C.
3.53 p. m. (Temperature 1,168° C.) Radius of stirring circle 2½ inches (B′ fig. 35).
4.02 p. m. Temperature, 1,156° C.
4.13 p. m. (Temperature 1,138° C.) Stirring stopped (C′ fig. 35).
4.18 p. m. Pot out.

Fenner finds that for the borosilicate crown (analysis 10, Table 4) and for the barium flint (analysis 101, Table 4) the best temperatures at which to remove the pot from the furnace are 1,050° C and 975° C, respectively. In the ordinary flint series the higher the lead content of a glass, the lower the temperature at which it is advisable to remove the pot of molten glass.

As soon as the optimum temperature for the removal of the pot has been reached, a definite procedure is followed in order to get the pot out of the furnace as quickly as possible; each man is given definite duties to perform and does these day after day. The stirrer is stopped; the clay stirring tube is brought slowly by means of the screw feed of the stirring machine to the side of the pot, where it is grasped and held in position by a forked tool while the water-cooled stirring rod is disengaged. The stirring rod is removed, the stirring machine pushed out of the way, the clay-stirring tube hooked against the side of the pot in an upright position by a heavy U-shaped iron rod, one end of which is inserted into the tube opening while the other end hangs down over the outer edge of the pot. An alternative method is to withdraw the stirring tube entirely from the melt by lifting it with the forked tool very slowly until it slips over the rim of

the pot. The tuille is now raised about a foot; the pot is commonly so tightly stuck to the siege that it has to be pried loose from it by means of a heavy iron bar acting as a lever on a low iron-block fulcrum placed on the siege in front of the pot; in this operation care is taken not to jerk or tip the pot violently, but rather to raise it slowly. The tuille is now raised high, the pot wagon is wheeled into place, the pot is grasped by the tongs or tine of the pot wagon, the counterweights are slid along the pot-wagon arm until the pot is practically counterbalanced. The pot is lifted gently and without jerks and jarring from the siege and wheeled out (fig. 36) on the floor of the furnace hall where it is placed on a support of fire-clay blocks. (Fig. 37.)

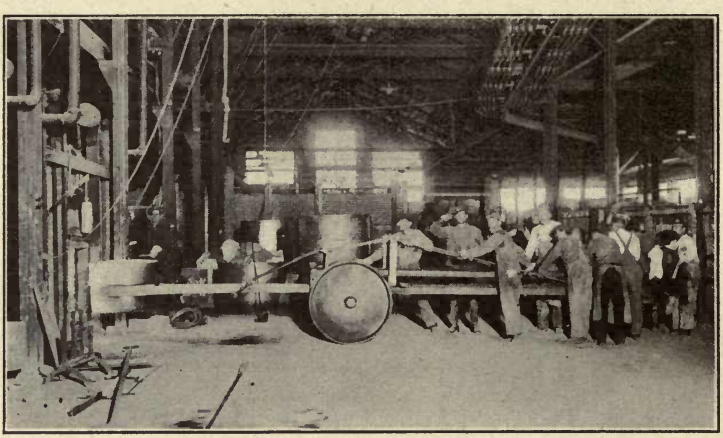

FIG. 36.—Removal of pot of molten glass from the melting furnace. Note the "whiskers" on the bottom of the pot; these are from the siege (floor) of the furuace to which the pot was stuck. (Photograph by J. Harper Snapp at the plant of the Bausch & Lomb Optical Co.)

The siege of the furnace is now scraped and leveled preparatory to the introduction of a fresh pot which is removed from a pot arch where it has been gradually heating for several days. (Fig. 32.) The new pot is removed from the pot arch by the pot wagon and placed in correct position in the melting furnace; the furnace tuille is lowered and sealed and the gas is turned on preparatory to baking the new pot at a very high temperature.

In the meantime the pot of molten glass has been cooling down in the open air. (Fig. 37.) Although the molten glass has not changed its appearance noticeably and is apparently still red hot, a hard crust has formed on the surface which may show an incipient shrinkage crack. It is moved either into the empty hot pot arch from which the fresh pot was removed or it is covered with an insulating cap which retards the rate of cooling, so that when cooled to room temperature the glass is fissured properly and is not highly strained.

This part of the glass-melting process, like the pouring of glass and rolling the molten mass into long sheets in the plate-glass industry, is the most spectacular part of the manufacturing process. The red hot, fuming pot of molten glass radiating such intense heat that the novice is fearful to approach very near to it creates an impression which is not soon forgotten.

SCHEDULE OF FURNACE OPERATIONS.

In the factory production of optical glass a definite schedule of the operations and temperatures is followed for each type of glass;

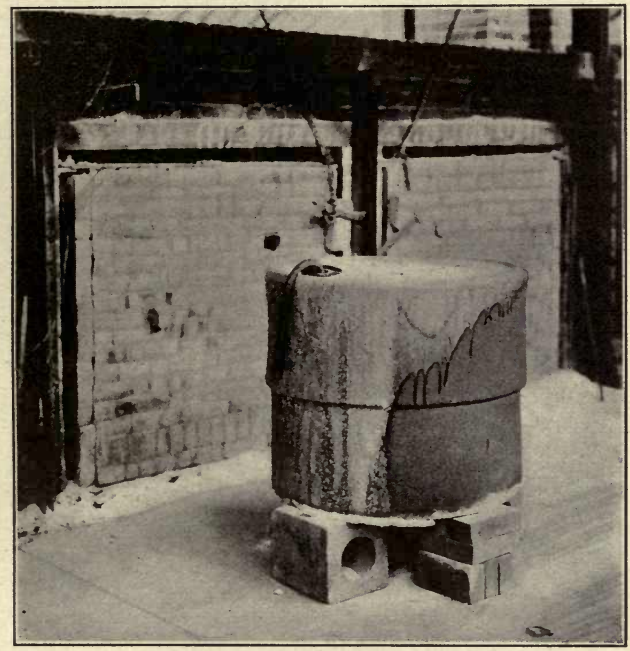

FIG. 37.—Pot of molten glass cooling down after removal from melting furnace and before insertion into cooling arch or being covered by insulating cap. Note the marks left by the molten glass which has spilled over the pot during the hand-stirring operations. (Photograph by J. Harper Snapp at the plant of the Spencer Lens Co.)

the schedules are different for different types of glass and a detailed record is kept of the treatment accorded each melting pot and each glass batch from the time it entered the furnace hall as raw batch to that of its delivery as raw glass to the inspection room. The schedule of furnace operations depends somewhat on the size of the glass plant and the attitude of the manager. Ordinarily it is convenient under present-day labor conditions to arrange the schedule so that the pots are removed from the furnaces during the afternoon of each day; this means either a 48-hour or a 24-hour schedule. If the plant is a large one and labor is always at hand, an intermediate schedule of 27, 30, or 36 hours may be followed to advantage.

In figure 38 five different schedules are presented in graphical form. In this figure the curves are not superimposed and referred to the same zero ordinate; but for the sake of clearness, the temperature scale for each curve is shifted 100° C. (one scale unit) above the curve next below it. Good glass can be, and has been, produced by each schedule; in fact, considerable leeway is permissible in the furnace schedule, providing certain fundamental principles are not violated.

The curves of figure 38 are self-explanatory and are taken to illustrate different types of practice at the different plants where different

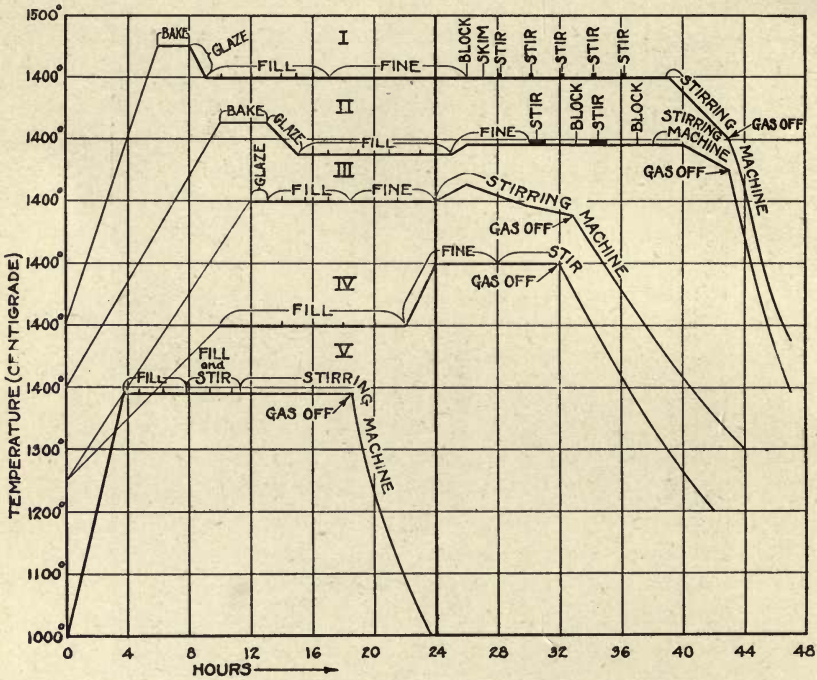

FIG. 38.—Curves showing different melting-furnace schedules for a medium flint glass as followed at different times at different plants. In this figure the plan has been followed of separating each curve from the next lower curve by one scale interval of 100° C. instead of superimposing the five curves. For this reason the temperature 1,400° C. is repeated five times on the vertical scale.

labor and furnace conditions prevailed. The curves represent the schedule for a flint glass of refractive index about 1.61 and containing about 45 per cent lead oxide (PbO).

The 24-hour schedule of melting optical glass.—During the latter months of the war, from September, 1918, a shortened glass-melting schedule was introduced by Dr. G. W. Morey, of the Geophysical Laboratory, at the plant of the Spencer Lens Co. This schedule is based on certain logical improvements in glass-melting practice, and is described here in a special section in order that the principles on which it is based may receive adequate emphasis.

Melts in open pots are heated chiefly by radiation from the crown of the furnace; the raw batch is melted accordingly, from the top downward; the easily fusible materials, such as the alkalies and lead oxide, melt first and trickle downward, leaving the sand and less fusible materials to sinter together in the upper layers and thus impeding their rapid solution. The result is an accumulation of extremely active chemicals, as alkali carbonates and nitrates, and of heavy fluxes, as lead oxide, on the bottom and lower sides of the pot which are thereby energetically attacked. The melting of the highly siliceous and viscous upper layers becomes under these conditions a slow and hampered process. In spite of the care taken in the batch room to mix the batch thoroughly, inhomogeneity is thus introduced, by differential melting, at the outset of the melting process. These differences in composition between top and bottom of the melt are, of course, eliminated later by stirring, but they can be avoided to a large extent by stirring the melt during the latter half of the pot-filling period when there is enough material in the pot to support the stirrer in an upright position during hand stirring. The melt should be stirred after each fill in order to insure uniform and rapid distribution of the fresh raw batch through the melt, and thus to expedite solution and to prevent segregation of the fluxes by gravitative differentiation. This is the first change in procedure adopted by Morey; it increases the rate of solution of the batch and lessens to a marked degree the inhomogeneity arising from differential melting and gravitational settling of the readily fusible materials. Incidentally some hours are saved by this procedure and the melting pot is attacked less than under the old schedule.

The second improvement applies to the "fining" of the glass and seeks to accelerate the escape of bubbles and seeds from the melt by continuous stirring during the fining period. This is best accomplished by machine stirring with a combined circular or spiral and an up-and-down movement. The bubbles result from the decomposition especially of the alkali-carbonates and nitrates. It is common practice to hold the melt at a high temperature during the fining period to increase its fluidity and thus to facilitate the rise of the escaping bubbles to the surface. In the plate-glass industry blocking is used near the end of the fining period to aid in washing out the small bubbles in the melt. In optical glass manufacture the usual procedure is to employ intermittent hand stirring with subsequent rest periods during which the melt attains a high and fairly uniform temperature throughout. The attainment of adequately high and uniform temperatures is extremely difficult with continuous stirring.

The 24-hour schedule requires for its successful application highly efficient furnaces and gas of good heating quality; the preliminary baking of the pot is best done in a pot arch specially constructed for the attainment of high temperatures.

With the shortened period of exposure of the pot to the furnace temperatures, there is less pot solution and hence greater transparency and freedom from color of the glass and also less chance for the presence of pot stones. The new schedule represents an appreciable saving in time and operating costs and also a marked increase in the rate of production per melting furnace.

The following schedule for the melting of a medium flint of $n_D = 1.617$ and $\nu = 36.5$ is given by Morey [25] as an illustration. In this schedule the time is recorded only from that of the first cullet fill. Slightly different schedules are followed for other types of glasses.

Schedule for M F_2 glass.

Hours.	
0.00	Add cullet (1,390° C.).
1.00	Fill pot three-quarters full of batch.
2.30	Fill pot with batch.
4.00	Hand stir, fill pot with batch.
5.30	Hand stir, fill pot with batch.
7.00	Hand stir, fill pot with batch.
7.30	Stirring machine on.
15.00	Gas off.

In the practical application of the schedule for this and other types of glass strict attention to details must be given. The schedules are closely timed and the furnaces must be kept in the best running condition.

EXPERIMENTS WITH STIRRED AND UNSTIRRED POTS OF OPTICAL GLASS.

The following experiments are of interest because of their bearing on the general functions of stirring in optical glass. (Experiments described in Report No. 4 for the week ending May 26, 1917.) Four small open pots were filled each with a light flint batch of the following composition in kilograms: Sand, 3.000; red lead, 1.920; potassium carbonate, 0.783; potassium nitrate, 0.237. These pots were held for different periods of time at about 1,400° C. The first pot was not stirred and was removed after exposure to this temperature for 8 hours; the second pot, also not stirred, was removed after 12 hours; the third pot was removed after 15½ hours, including a stirring period of 1½ hours; the fourth was removed after 19 hours, including a 2-hour stirring period. The glass produced by this treatment in small pots is of course valueless optically. It abounds in bubbles, is not highly transparent, and is only fairly white in color. Especially interesting are the two unstirred pots. The first pot taken out after 8 hours melting is full of small bubbles (seeds) and stones. Each stone and some of the bubbles are seen to have left, in their upward passage through the glass, a tail such that in the aggregate they resemble a

[25] Jour. Am. Ceram. Soc. 2, 150, 1919.

company of tadpoles marching in parallel columns toward the upper surface. The stones are evidently silica (sand) in process of assimilation. (Fig. 39.)[26]

Geologically this phenomenon is interesting because it presents the phenomenon of gravity differentiation in place, thus giving rise to a separation into a top layer rich in silica and poor in lead (about 20 per cent lead) and a bottom layer rich in lead (about 46 per cent lead). The distribution of the layers, as determined by refractive index measurements, is shown in figures 40*a* to *d*. A comparison of pots 1 and 2 (fig. 40*b*) shows that the sharp gradations from the top surface to the central portion and also from the bottom layer up to the center,

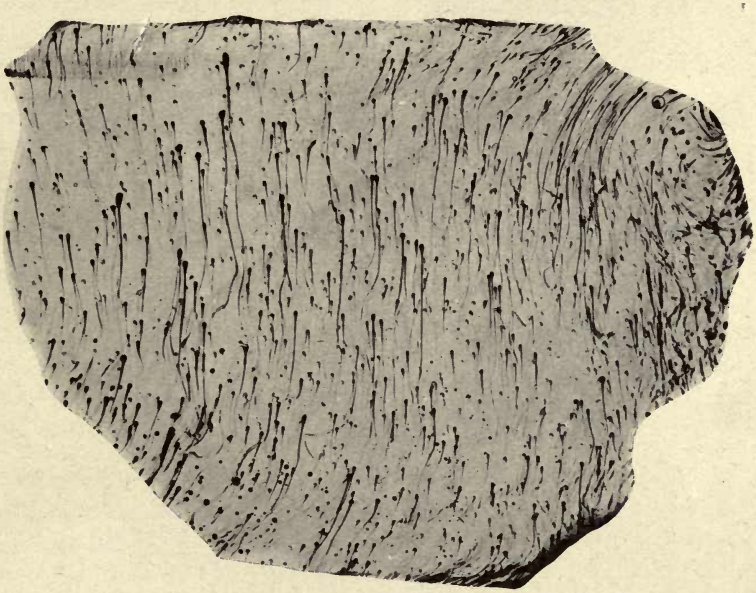

FIG. 39.—Photograph of sand grains in process of solution in a small melt of optical glass.

as represented graphically in figure 40*e*, are less pronounced in pot 2. In other words, diffusion in the course of four hours additional heating has tended to reduce the sharp differences in concentration in the melt. Convection probably aided to a certain extent; but the distribution of the material in the pot does not indicate pronounced convection currents.

In the stirred pots the distribution of uniform glass is remarkable. The stirring was poorly done; the stirrer scraped the bottom and sides repeatedly; and yet, except for a lower refracting surface film not over 1 millimeter thick, there is little variation in composition from top to bottom or from side to side. The persistence of the lower refracting surface film proves that there is appreciable volatilization

[26] Experiments carried out by N. L. Bowen and the writer. See N. L. Bowen. Jour. Wash. Acad. Sci. 8, 88–93, 1918.

of lead and alkalies and that the upper layer is richer in silica. The unstirred pot of glass is not unlike a layer cake in its refractive index distribution. The surfaces of equal refractive index are approximately planes parallel with the upper surface. This being the case

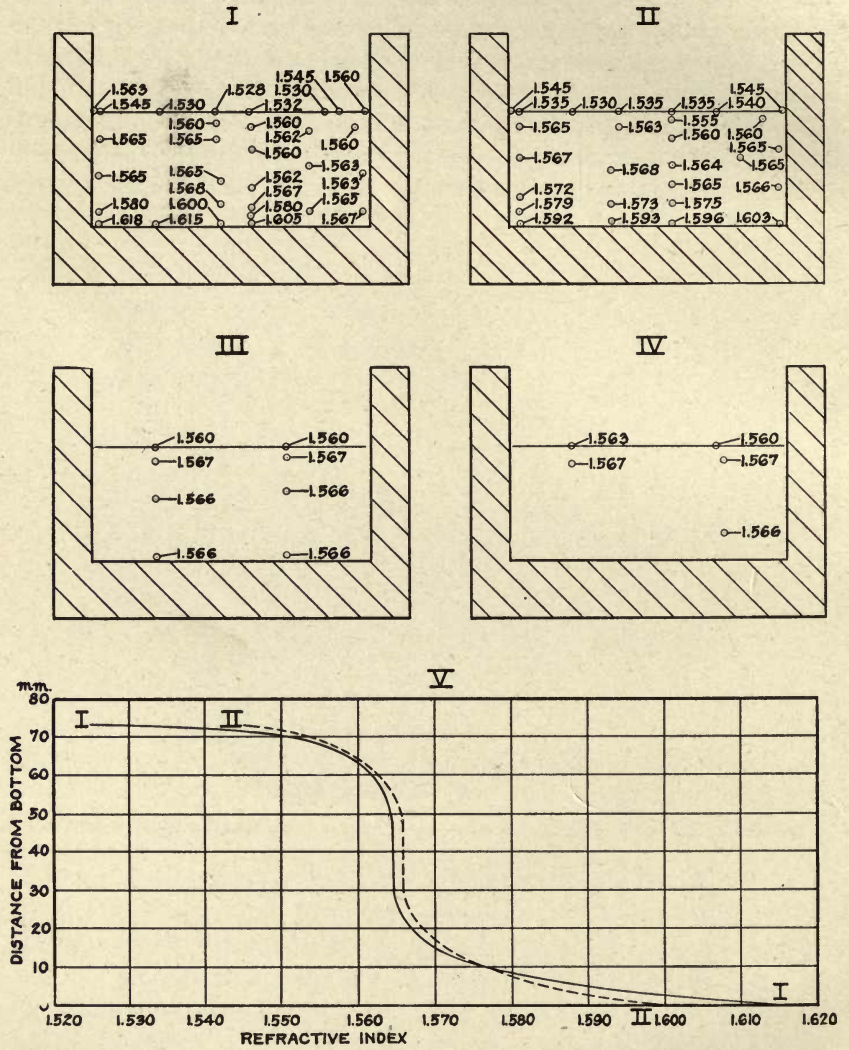

FIG. 40.—Diagram illustrating the changes in refractive index, n_D, in small pot melts of a light flint batch. Pot 1 was heated at 1,400° C. for 8 hours, but was not stirred; pot 2 was heated at 1,400° C. for 12 hours, also not stirred; pot 31 was heated at 1,400° C. for 15½ hours, including a stirring period of 1½ hours; pot 4 was heated at 1,400° C. for 19 hours, including a 2-hour stirring period. The curves I and II illustrate the changes in refractive index, n_D, from top to bottom of the melts of pots 1 and 2.

it appears that an energetic up-and-down stirring during the first part of the melting process is essential in order to render the mass homogeneous. The bottom of the pot should be thoroughly swept by currents of the molten glass during this period.

An illustration (weekly report No. 6, June 9, 1917) of the degree of uniformity attained in a large pot (No. 472) of light flint ($n_D = 1.579$, $\nu = 41.0$, PbO = 36.5 per cent) after two 15-minute periods of hand stirring during each two hours is given in figure 41. After these periods of stirring the pot began to leak and was removed from the furnace and allowed to cool in the open air. Samples were taken from the different parts of this pot of glass and were measured by the immersion method. It is remarkable that so short a period of stirring should result in so thorough mixing of the melt. Except for the top-film layer which is always lower in refractivity and the sides and bottom which were contaminated with dissolved pot, the refractive indices do not vary more than one or two in the third decimal place.

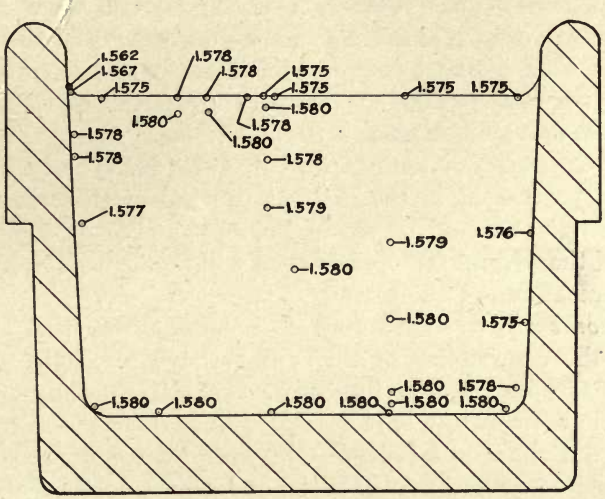

FIG. 41.—Diagram illustrating changes in refractive index, n_D, at different parts of a pot of light flint glass after two hand-stirring periods of 15 minutes each Pot No. 472, Bausch & Lomb Optical Co.

In view of the fact that fine striæ are caused by only slight differences in refractive index, these measurements indicate that the function of long-continued stirring is chiefly to remove the slight differences in composition which are still present and are constantly arising because of volatilization and of pot solution, which diffusion smooths out only slowly.

THE COOLING OF THE MELT.

If the operations up to this point have been successful, the pot of molten glass, on removal from the furnace, is sensibly homogeneous except for the peripheral portions where, as a result of selective volatilization at the surface and of pot solution along the sides and bottom, the melt contains more silica (and possibly alumina from the pot) and is more viscous. The temperature of the melt is, moreover, fairly uniform except for the bottom in contact with the thick, over-

heated base of the pot which has had little chance to cool except by radiation through the melt. Measurements of the temperature of the furnace floor (siege) immediately after removal of the pot show that its temperature, and hence that of the base of the pot, is from 50° to 100° C. higher than that of the metal in the pot. There is, of course, a slight temperature difference between the center and margins of the melt as a result of its continued cooling. The molten glass has now the consistency of thick heavy syrup; and with further fall in temperature its viscosity increases rapidly.

The problem which confronts the glassmaker at this stage is to avoid any tendency which may cause the marginal portions to stream into the body of the melt; also to avoid crystallization phenomena and the formation of bubbles. A lesson learned from experience and not adequately realized by many glassmakers is the fact that during the time interval between the cessation of stirring and the cooling of the melt to 600° C. (temperature fall from 1,000° to 600° C. approximately) much glass is needlessly lost. Were it possible to maintain, through the temperature drop to 600° C., the degree of homogeneity attained in the melt at the end of the stirring period much more glass would be saved than is at present the case. An analysis of the several factors involved will render this clear and suggest the precautions to be taken.

Convection currents.—On removal of the pot from the furnace the melt has the consistency of thick, heavy syrup. With further fall in temperature its viscosity increases so rapidly that any appreciable difference in temperature between different parts of the melt produces a distinct difference in density. Convection currents are set up as a result of the downward flow of cooler and denser portions of the melt, and are serious because they generate heavy striæ, cords, and ribbons in the melt, thereby rendering much of it useless. The fact, moreover, of excess heat at the base of the pot favors an upward trend of the bottom layers of the melt, and their stream lines may pass into the central core of the melt and thus cause striæ.

In a viscous melt the rate of transfer of material by convection is relatively slow and decreases with fall in temperature and consequent rise in viscosity. The obvious method to reduce convection currents is to cool rapidly and uniformly from 1,000° to 600° C. from the margins of the melt toward the center. The bottom of the pot is, however, much hotter and thicker than the sides; it acts somewhat as a heat reservoir and cools less slowly than the sides or the surface of the melt. An effort should be made to expedite the cooling of the base by allowing a free or forced circulation of air to play around it. The surface of the melt, on the other hand, chills more rapidly in direct contact with the air than either the sides or the bottom; a tendency is thereby set up for its cooled, and hence denser,

material to sink toward the bottom and thus to introduce striæ. Its rate of cooling should accordingly be retarded by some method of heat insulation, such as covering it with a layer several inches (commonly 4) thick of light insulating material, as diatomaceous earth.[27]

Fine siliceous powder of this nature shows no tendency to sink into the melt and insulates most effectively. Much good glass has been produced, it is true, without the use of an insulating surface layer; but in this case the pot with melt is allowed to remain in the open air for a short period only, 15 to 30 minutes, and is then inserted into a previously heated pot arch from which the empty pot was taken to replace the finished pot removed from the melting furnace. The temperature of the heated air in the pot arch is high; hence the tendency for the surface to cool with extreme rapidity is practically annulled.

Vacuum bubbles.—There is still another reason for retarding the rate of cooling of the surface of the melt. Glass, on cooling, shrinks, and at low temperatures its viscosity becomes so great that it behaves practically as an elastic solid. If the surface of the melt cools rapidly in the open air, a hard crust forms in the course of half an hour while the center remains nearly as hot as it was when it left the furnace. The surface contracts on cooling, and cracks may begin to form. On further cooling the center tends to draw away from the unyielding crust. If the tensional stresses are not then relieved by cracks and fissures, both horizontal and vertical, large bubbles, called vacuum bubbles, may form and ruin an appreciable quantity of glass. This phenomenon is not so common in large pot melts because in them cracks generally do develop and resemble then in all details the jointing phenomena of lava flows. In small experimental pot melts cracks are not so likely to form and in them vacuum bubbles are of common occurrence. The bubbles can be avoided either by insulating the surface of the melt with a layer of diatomaceous earth or by breaking through the surface crust with a pointed iron rod, thus puncturing the seal established by the crust.

Crystallization phenomena.[28]—The phenomena of crystallization in optical glasses are so important and so unwelcome to the glassmaker that a practical understanding of the principles involved is essential if crystallization or other precipitation is to be avoided. At high temperatures optical glass is a mobile liquid; with rise in temperature its fluidity increases and it behaves in all respects like an ordinary liquid or like molten metal; with fall in temperature its viscosity

[27] This method was first applied by the Geophysical Laboratory and is described in detail by H. S. Roberts in "The cooling of optical glass melts." Jour. Amer. Ceram. Soc., 2, 543–563, 1919.

[28] These phenomena are discussed in detail by N. L. Bowen in "Devitrification of glass," Jour. Amer. Ceram. Soc., 2, 261–281, 1919.

increases so rapidly (doubling for each drop of 8° to 10° C. in temperature) that at room temperatures its viscosity is nearly infinite and it behaves practically as an elastic solid.

Glass has no definite melting temperature, but rather a temperature range over which it softens rapidly and becomes a fluid in the ordinary sense of the word. At all temperatures glass is a solution; at high temperatures a mobile or fluent solution, at low temperatures an immobile solution. As a solution glass is subject to the general laws of solutions. A solution such as sugar and water is able at a given temperature to dissolve a certain quantity of sugar; if now the temperature be raised, the solution is found capable of dissolving still more sugar. The saturation limit rises, in this case, with rise in temperature; a solution of a given composition, saturated with respect to a given substance at a high temperature, may be greatly supersaturated with it at a lower temperature. The solution is then not in equilibrium and seeks to attain equilibrium by the precipitation of a certain amount of the phase which is present in excess.

Experience with silicate melts of the general type of glass melts has shown that the silicate components are miscible in all proportions and that, on cooling from a high temperature, the solution becomes supersaturated, in general, first with respect to one phase, then to two, and so on. As soon as the saturation limit of any one phase is reached a tendency is set up for this phase to crystallize out. There are, however, certain factors which tend to counteract this tendency. Crystallization in each case means the orderly arrangement of atoms or molecules in space; the rate of building up of each crystal structure depends on a number of factors, such as degree of supersaturation of the phase in the solution, the viscosity of the solution (function of composition and temperature), rate of transfer of material in the solution, crystallizing ability of the crystal phase, etc. The molecules in the solution must wander (diffuse) to the crystal nucleus or growing crystal and this takes time; if the viscosity of the solution at this temperature is high, the rate of transfer of the molecules is slow; furthermore the tendency toward crystallization is nil above the temperature at which the saturation limit is reached; not far below it, the crystallizing tendency increases rapidly, reaches a maximum, and then, because of the greatly increased viscosity, grows less and finally practically disappears when the glass becomes hyperviscous. The power of crystallization of different substances varies greatly. The usual measure for the power of crystallization at a given temperature is the number of crystal nuclei formed in unit time in unit volume. A substance of high crystallizing power can not be cooled much below its saturation limit before crystallization sets in; one of low crystallizing power is readily undercooled and may only with difficulty be made to crystallize even under the most favorable conditions.

The primary object in optical glass manufacture is to obtain homogeneous, colorless glasses of definite optical constants. In seeking to attain these ends batch-compositions may be tried out which are greatly supersaturated with respect to one of the phases, and this, on the cooling of the melt, crystallizes out and ruins the product.

In setting up trial batches for glasses of a given composition, it is advisable in each case to make small trial melts and to hold these at different temperatures between 800° and 1,100° C. in order to ascertain their crystallizing tendencies. In the case of the crystallization

FIG. 42.—Fracture section across a pot of light flint glass. Pot No. 594, B. & L. White rim around edge of glass consists of sillimanite. Pot shows little evidence of attack by glass melt.

of one or more phases these can be determined by petrographic microscope methods.

Ordinarily the primary phase to appear is silica (in the form of tridymite or cristobalite), or calcium metasilicate (as wollastonite). In glasses very high in lead, lead metasilicate may be precipitated; in glasses high in barium, barium disilicate has been observed to crystallize in the form of skeleton crystals hexagonal in shape. Near the margins of the glass melt, adjacent to the clay pot walls, a thin white layer is not uncommon (fig. 42); it consists generally of an interlacing aggregate of crystallized aluminium metasilicate (needles of sillimanite).

In case crystallization (devitrification) of the glass melt occurs within the time-temperature limits of the glassmaking schedule, either the amount of the excess phase must be reduced in the batch or the viscosity of the melt should be changed by the addition of a small amount of alumina (rarely magnesia) or by the substitution of potassium for sodium, or a smaller melting pot may be taken in order to expedite the rate of cooling of the melt. The fact that a melt can be successfully made in a 36-inch pot, holding half a ton of glass, does not signify that the same batch composition will be satisfactory in a 49-inch pot, holding a ton of glass.

The time factor has a most important bearing on the crystallization of glass melts. Molten silicates have relatively large heat capacities and are poor conductors of heat; large masses can not therefore be cooled at a rapid rate even under the most favorable conditions. This means that the larger the pot, the more care must be taken to avoid crystallization. The experimental melts made for the purpose of testing out a batch composition should be held at given temperatures for lengths of time corresponding to those actually obtaining in the glass pots used.

The types of crystallization which develop in the melt depend not only on the kind of substance which is precipitated, but also on the temperature and the composition of the melt. Thus single isolated crystals of barium-disilicate were formed [29] toward the end of the stirring period (1,100° C.) as crystal skeletons in a melt of light barium crown. These were avoided in later melts by reducing the percentage amount of barium oxide in the batch to the extent that the temperature at which the melt became supersaturated with respect to barium disilicate was lowered below that of the final stirring period. The amount of reduction was computed, after the melting temperature of pure barium disilicate had been found by measurement to be 1,426° C., by assuming, as a first approximation, that the lowering of the saturation temperature was directly proportional to the amount of barium disilicate present. As the required change of composition was only slight and sufficient to lower the saturation limit from 1,100° to about 1,030° C. this assumption was justified. Thus the saturation limit was reduced from 1,426° (pure barium disilicate) to 1,100° C. by a reduction of barium disilicate from 100 per cent to 57 per cent. On the assumption of a linear relation between composition and temperature at the saturation limit, this signifies a lowering of about 7° C. in the temperature of saturation per reduction of 1 per cent barium disilicate. But since all saturation-temperature curves which have been determined in silicate melts are concave toward the origin in a temperature-concentration diagram, the gradient of the curve is likely to be somewhat steeper than a straight

[29] N. L. Bowen. Jour. Wash. Acad. Sci., 8, 265–268, 1918.

line so far away from the pure compound with the result that a reduction of 1 per cent in barium disilicate would probably lower this saturation limit more than 7° and possibly as much as 15° C. Actual test showed that a reduction of 5 per cent in the amount of barium disilicate present in the batch eliminated the presence of its crystals from the melt under the given conditions of melting. Similar methods for the adjustment of batch composition are followed with melts of different compositions in which crystallization may appear.

In ordinary types of optical glass silica is present in excess with the result that it is first to crystallize out from the melt usually in the form of radial spherulites of cristobalite or tridymite. Crystallization in pots of optical glass begins ordinarily at the top surface and sides and proceeds inwards. The surface of the melt, because of volatilization, becomes richer in silica which is then the primary phase to crystallize out. The surface of a cooled pot of glass, such as borosilicate crown or barium crown, is commonly covered with fine, exceedingly thin crystallites, visible only under a hand-lens and resembling hexagonal snowflakes. The surface, if examined closely, is seen to be covered with a hexagonal network of lines which are obviously the directions of tenuous crystal growth in the thin surface film.

If the cooling of the glass pot is not conducted with sufficient rapidity the crystallites in the surface film extend inward into the glass mass; white radial spherulites are formed. In the case of borosilicate crown, a crust of radial spherulites of crystallized silica 1 to 2 millimeters thick, occurs almost invariably around the margins of the surface of the melt. Crystallization of this kind is not serious from the glassmaker's standpoint because of the relatively small amount of glass wasted. In the case of the molding of glass, surface crystallization may be serious because the crystallized crust is much harder than the glass itself and offers serious resistance to the grinding wheels during the plate-grinding operations, so serious in fact that every effort should be made to regulate the temperature in the molding kilns so that crystalline crusts are not formed on plates of borosilicate or barium crowns. In the flint glasses the danger from surface crystallization is much less.

Other substances which may crystallize out of certain melts are calcium metasilicate (in the form of wollastonite), lead metasilicate, and aluminum metasilicate as sillimanite. The first two occur commonly as radial spherulites, like rounded pellets up to 1 centimeter in diameter throughout the melt. Because of the differences in their rates of contraction as compared with that of the enveloping glass, a large amount of strain is set up in the glass; conical cracks may develop and extend for a short distance from the radial spherulite into the glass. The presence of a crystallization body in a lens or prism is sufficient cause for its rejection.

Cloudiness or opalescence.—Still another phenomenon, allied to precipitation, may arise during the cooling process and ruin the entire pot of glass. In certain types of glass, especially in the flint series, there is a tendency for the melt to turn milky or cloudy during the cooling-down period. Turbidity of this kind in optical glass is a very serious defect and renders it useless for optical purposes. The cloudiness ordinarily develops at the sides and top of a crucible of glass and proceeds inward from the margins. The factors involved in this problem are not entirely clear, but the following facts are significant: Proofs, taken at high temperatures, of a melt which later becomes turbid, are perfectly clear and show no trace of milkiness; these proofs may develop cloudiness, however, on reheating to temperatures somewhat above the softening point of the glass (800° to 1,000° C.). If held for long periods of time (several days) at this temperature, crystallites of a low refracting substance, possibly silica in the form of tridymite or cristobalite, develop. The presence of these crystallites does not definitely prove that the substance which causes the milkiness is excess silica. In the milky glass the precipitated material is held in suspension and the particles, whatever their nature may be, whether silica, lead sulphate, lead chloride, boron silicate, or arsenic oxide, may serve as nuclei around which the radial spherulites of crystallized silica cluster when the glass is maintained at 900° to 1,000° C. for a long period of time. A thin plate of opalescent light flint examined under the ultra microscope showed the presence of innumerable particles suspended in the glass. The phenomenon is therefore one of precipitation either of colloidal particles or of submicroscopic crystallites. A chemical analysis of a fragment of milky glass showed the presence of 0.146 per cent SO_3; this is equivalent to 0.553 per cent lead sulphate.[30]

Factory experience proves that the presence of sulphates and chlorides in the raw materials, especially in the potassium carbonate, favors the formation of opalescence. In England[31] the same trouble with cloudiness in flint glass for tableware purposes was experienced during the war and was ascribed to the presence of sulphates and chlorides in the poorer grade of available potassium carbonate. Experience has proved that a slight change in the composition of the batch may greatly decrease the probability of the occurrence of milkiness; thus light flint containing 2 per cent boron oxide is especially liable to turn milky; it is possible that the presence of this oxide favors the development of cloudiness in this flint. It has been found that fining at a high temperature (increased volatilization of certain components), thorough stirring, and rapid cooling of the melt thorough the tempera-

[30] See article by Fenner and Ferguson "On the effect of certain impurities in causing milkiness in optical glass." Jour. Am. Ceram. Soc., I, 468, 1918.

[31] Cauwood and Turner, Jour. Soc. Glass Technology, I, 187, 1917.

ture range, in which precipitation is liable to occur, are advisable. The addition of 1 or 2 per cent of alumina to the glass aids as a preventative; this oxide tends to increase the viscosity of many glass melts and its presence then necessarily raises their fining temperatures. Long-continued heating (24 hours),[32] at 950° C. in a platinum resistance furnace, of a light flint glass containing 2 per cent alumina which was fined at the usual fining temperature of the light flints, proved that glass of this composition did not become milky; whereas the same light flint without the addition of alumina did become milky under the same treatment, thus proving that alumina tends to hinder to some extent the milky precipitation. Observations have proved that by reheating milky flint to a temperature of 1,100° C. it can be rendered clear, but that under these conditions bubbles develop and render the glass useless.

In this problem of milky glass we are confronted with the precipitation of some substance possibly colloidal in nature; it is probable that the opalescent effect in the light flints may be produced by different substances. The presence of sulphates and chlorides in the batch favors its formation; thus, light flint glass made from potassium carbonate containing 0.1 per cent SO_3 was clear and of good quality; glass similar in composition, but made from potassium carbonate containing 0.75 per cent SO_3, turned milky on cooling; while glass made from potassium carbonate containing 0.4 per cent SO_3 became milky only at the margins of the crucible. In medium flints the presence of a relatively large amount of arsenic oxide may also cause cloudiness and should be avoided. That the rate of cooling is an important factor is proved by the fact that large pots containing a ton of optical glass are more liable to become milky on cooling than small pots half this size.

Whatever the precipitate is, the solubility relations are such that at a high temperature the solution is not supersaturated, but on cooling it becomes saturated with respect to some substance and, with still further lowering of the temperature, precipitation begins if sufficient time be allowed for it during the cooling process; the temperature range within which precipitation is liable to occur is 500° to 1,000° C. It is possible that the substance in the light flints is silica or lead sulphate, or lead chloride which is only slightly soluble in silicates. On fining the glass at high temperatures the volatilization of the sulphates and chlorides increases; such heating may also inhibit the formation of the colloidal particles which on cooling produce opalescence; the presence of small amounts of boron oxide seems to favor the formation of such clusters; the presence of alumina tends to hinder their formation.

[32] Experiment by C. N. Fenner.

In other branches of glass manufacture milky glass is produced purposely by the addition of certain substances, such as phosphates and fluorides, which are relatively insoluble in the glass melt. When chilled quickly, these glasses may remain clear, but on reheating and cooling down slowly through a temperature range from 800° to 400° C. they become cloudy. The precipitation in opalescent glasses indicates the grouping of certain constituents of the melt into particles of at least colloidal size such that they have an appreciable diffracting effect on light waves in the visible spectrum.

Closely allied to the development of milky glass in the light flints is the behavior of red and yellow glasses at the annealing temperatures. If a glass, colored with cadmium sulphide, selenium, copper ruby, or gold ruby, be chilled rapidly from a high temperature the intensity of its coloration is relatively slight; but if the glass be cooled slowly from high temperatures or be reheated after chilling, it becomes deeply colored, the more intense colors being deep red. This behavior indicates a shift of a strong absorption band from the ultra-violet into the violet or blue. There is evidently a shift in molecular grouping or aggregation within the solution such that the grouping stable during the annealing range absorbs the blue end of the spectrum; this regrouping takes place while the glass is still relatively rigid.

Blue and green glasses do not show this pronounced change in color absorption in the visible spectrum on change in heat treatment. In all such cases involving change in color, or the development of opalescence and milkiness, there is probably a selective grouping and aggregation of certain of the atoms or molecules into particles which, though still submicroscopic in size, have an effect on transmitted light waves; the rate and character of this selective grouping is dependent, moreover, on the temperature conditions; the grouping can be practically suppressed by cooling down through the critical temperature range so rapidly that sufficient time is not available for the completion of the process.

The fact that the intensity of coloration in the yellow and red glasses is markedly dependent on the heat treatment may have an important bearing on the transmission in optical glasses. Ferric iron colors glasses yellow and absorbs a large part of the ultra-violet; with increase in ferrous iron content the color of the glass shifts to the green and even to the blue in the barium glasses; glasses colored with ferrous iron oxide are good infra-red absorbers. There are indications that the intensity of coloration of glasses containing iron in the ferric state varies with the heat treatment and that the reheating of such glasses for annealing or pressing tends to lower the transmission.

Little is definitely known regarding the phenomena involved in the formation of milky and opal glasses and of red and yellow colored glasses. In the milky glasses swarms of particles of some substance or substances, probably excess silica either in the colloidal state or as embryonic crystals of tridymite or of cristobalite, are precipitated and are held in suspension in the molten glass. It has been found that the presence of minute quantities of alkali sulphates or alkali chlorides or both tend to favor this precipitation, acting in this respect after the manner of "catalyzers." Be the precipitate and the causes therefor what they may, the factory practice to be followed to avoid the occurrence of milkiness is to use materials of high chemical purity, especially potassium carbonate containing less than 0.3 per cent SO_3 and 2 per cent Cl, to fine at high temperatures somewhat above 1,400° C., to stir the melt thoroughly for as long a period as possible, and to cool rapidly through the temperature range of precipitation.

The identification of crystallites in optical glass.—The identification of crystallization bodies in optical glass is best accomplished by use of the petrographic microscope. Methods have been devised for the measurement of the optical constants of crystals in fine grained aggregates and have been employed for many years in routine work of this nature at the Geophysical Laboratory.[33] For the determination of any given "stone" in a glass it is broken out of the glass and crushed, by tapping with a pestle in an agate mortar, to a fine powder. A few particles of the powder are immersed in a small drop of liquid of known refractive index on a microscope object glass. A small glass cover slip is placed on the drop and the preparation is examined under the microscope. By the use of refractive liquids of different known refringences it is possible to ascertain with the petrographic microscope, the principal refractive indices of the substance or substances, in case more than one be present; also the principal birefringences of each substance, the general shape of its optical ellipsoid, its optical character, its optical axial angle, its pleochroism, etc. These properties enable the observer in most instances to identify the crystals. In view of the relatively small number of crystallization bodies, "stones," which may possibly occur in optical glass the measurement of the refractive indices alone generally suffices to identify the crystal. The optical properties of the several more common crystals in glass are the following:[34]

Silica (SiO_2) may appear in any one of three different forms, all of which are found in natural minerals, namely, quartz, tridymite, and cristobalite.

[33] F. E. Wright, The methods of petrographic microscope research. Publication 158, Carnegie Institution of Washington, 1911.

[34] See also N. L. Bowen, "The identification of 'stones' in glass." Jour. Amer. Ceram. Soc., I 594-605, 1918.

Quartz appears rarely and only as undissolved sand grains from the original batch. They occur as irregular rounded grains, are optically uniaxial and positive, birefringence medium with refractive indices, $\epsilon = 1.554$, $\omega = 1.545$.

Tridymite is similar in every respect to the natural mineral and appears in thin hexagonal-shaped plates of weak birefringence. Examined on edge these plates show parallel extinction and weak negative elongation. The refractive indices are: $\alpha = 1.469$, $\gamma = 1.473$. Interference figures are difficult to obtain because of the weak birefringence.

Cristobalite is the form stable [35] between 1,420° C, and its melting temperature 1,710° C. It occurs commonly in the form of skeletal crystals resembling the octahedral growths observed in copper, gold, and common salt. Its crystal aggregates are terminated in many instances with spear-shaped, octahedral endings and are not lath-shaped as in the case with tridymite. Its refractive indices are $\alpha = 1.484$, $\gamma = 1.487$. The birefringence is exceedingly weak. The higher refractive indices and different crystallographic development suffice to distinguish cristobalite from tridymite.

Calcium metasilicate ($CaSiO_3$) occurs commonly in the form of radial spherulites of the mineral wollastonite. Its needles extinguisn parallel to the direction of elongation and show either positive or negative elongation. The plane of the optic axes is normal to the elongation; optic axial angle small, optical character negative. Refractive indices are: $\alpha = 1.620$, $\gamma = 1.633$; birefringence, medium.

Sillimanite (Al_2SiO_5) occurs in radial spherulites and interlacing, lath-shaped aggregates. The individual crystals show parallel extinction and positive elongation. The refractive indices are relatively high, $\alpha = 1.660$, $\gamma = 1.681$; the birefringence is moderately strong. The crystals frequently exhibit a lower refracting core which may be the result of skeletal development of the laths.

Barium disilicate ($Ba\ Si_2O_5$). Crystals of this compound were first identified by Bowen [36] as orthorhombic. They occur as thin six-sided plates; extinguish parallel with negative elongation. Refractive indices $\alpha = 1.598$, $\gamma = 1.617$; birefringence moderately strong.

THE ANNEALING PERIOD.

On cooling to a dull red heat, the pot of molten glass becomes increasingly stiffer and with falling temperature acquires more and more the properties of a rigid solid. The rate of cooling is, however, not equal over different parts of the pot and the rates of contraction are correspondingly different; as a result internal stresses and strains

[35] C. N. Fenner, The stability relations of the silica minerals. Jour. Wash. Acad. Sci., 2, 471, 1912; Am. J. Sci. (4), 36, 331-384, 1913.

[36] Jour. Wash. Acad. Sci., 8, 265-268, 1918.

are set up. At higher temperatures from 700° C. down to 400° C. or lower the internal stresses are relieved by actual flow of the glass if it is allowed sufficient time to flow. The rate of release of the internal stresses is a function of the magnitude of the stresses and these in turn are caused by differences in the rates of cooling of different parts of the pot of glass. At higher temperatures the stresses are relieved by internal flow as rapidly as they are developed; at these temperatures the glass behaves as a viscous liquid and is unable to maintain shearing stresses for any length of time. Shearing stresses are relieved by actual flow of the melt. With falling temperatures the rate of release of internal stresses becomes slower and practically ceases at low temperatures; it fails, in short, to keep step with the temperature drop and hence the stresses persist and, unless relieved by stresses in the opposite direction, may continue indefinitely at room temperatures.

The factors which enter into the problem of the cooling and fracturing of a pot of optical glass are complex and at the present time are not adequately known to permit of its complete solution. The available information suffices, however, for the establishment of a fairly satisfactory manufacturing routine. The more important factors are:

(*a*) Change of viscosity of the different glasses with temperature.

(*b*) Rates of relief or relaxation times of internal stresses of different magnitudes at different temperatures.

(*c*) Changes in expansion coefficient with temperature.

(*d*) Temperature distribution within a cooling solid of the shape, dimensions, and thermal characteristics of an optical glass mass cooling in a clay pot.

These factors will now be considered in the order given.

(*a*) The most important recent investigation on the change of viscosity of glass with temperature is that of F. Twyman [37] whose experimental results showed that the mobility of most glasses through the critical range from 400° C. to 600° C. doubles for each 8° rise in temperature. In the form of an equation this statement reads

$$M = K \cdot 2^{\frac{\theta}{8}} \qquad (1)$$

or

$$M = 2^{\frac{\theta-\theta_o}{8}} = e^{\frac{\theta-\theta_o}{11.54}} = 10^{0.0376\cdot(\theta-\theta_o)}$$

in which M is the mobility (the converse of the viscosity), θ the temperature, and K and θ_o, constants dependent on the kinds of glass. Still more recent experiments by M. So,[38] Tool and Valasek,[39] Littleton and Roberts,[40] and Adams and Williamson [41] have corroborated the

[37] The annealing of glass, Jour. Soc. Glass Technology, **I**, 61–73, 1917.
[38] Phys. Math. Soc. Japan, **2**, 113–116, 1920, Math. Phys. Soc. Tokyo, Proc. **9**, 425–441, 1918.
[39] Bur. Standards Bull. No. 358, 1919.
[40] Jour. Opt. Soc. America, **IV**, 224–229, 1920.
[41] Jour. Franklin Institute, **190**, 597–632, 835–870, 1920.

results of Twyman and found that the mobility changes differently with different glasses and that it doubles for a rise in temperature of 7.9° C. to nearly 11° C., depending on the type of glass, the value being commonly higher for the crown glasses than for the flint series. These measurements of mobility were made by observing the rate of stretching, or of bending, or of twisting of glass rods under constant load at the different temperatures. As the temperature falls the mobility decreases so rapidly that mechanical methods are no longer practicable and recourse is had to optical methods.

Strain in glass signifies physical inhomogeneity and this finds expression in the effects which strained glass exerts on transmitted light waves that encounter different degrees of resistance according to the direction of their transmission. This difference gives rise to the phenomena of double refraction and these can be detected and measured by the use of polarized light and suitable accessory appliances. Early in the last century Brewster [42] discovered that in strained glass the resulting birefringence is proportional to the load; in other words, stress in a glass can be measured in terms of birefringence. Methods, based on the measurements of the birefringence in a piece of optical glass, have long been used and afford simple and satisfactory means to study strain in glass from ordinary temperatures up to the softening region of glasses. Commonly the path-difference between the two plane-plorized light waves is measured by means either of a graduated wedge, or of a Babinet compensator, or of other device of similar nature, either in white or monochromatic light; or the ellipticity of the emergent beam is determined in monochromatic light and the path difference is then computed from the ellipticity. Measurements by these methods have recently been published by Twyman,[43] Tool and Valasek,[39] Adams and Williamson,[44] and Littleton and Roberts,[45] and prove that the law given for the change of viscosity with temperature is valid for the change of rate of relief of stresses with temperature; except that in the case of birefringence the temperature interval required for a doubling of the rate is found to be somewhat smaller than that necessary for a doubling of the mobility when measured by mechanical methods. This discrepancy may, however, be due to the fact that measurements of the mechanical deformation are made at higher temperatures than those of the change in birefringence. The equation expressing the change in rate of relief of stress or the

[39] Bur. Standards Bull., No. 358, 1919.
[42] Philosophical Transactions, 1814.
[43] Jour. Soc. Glass Technology, I, 61–73, 1917.
[44] Jour. Opt. Soc. America, IV, 213–223, 1920.
[45] Jour. Opt. Soc. America IV, 224–229, 1920; Jour. Franklin Inst. 190, 597–632, 835–870, 1920.

change in relaxation time as measured by optical methods is accordingly

$$T=\frac{K_1}{M}=K\cdot 2^{\frac{-\theta}{8}}=2^{\frac{\theta_0-\theta}{8}}=2^{\frac{\theta_0-\theta}{N}}=10^{0.0376\cdot(\theta_0-\theta)}=e^{\frac{\theta_0-\theta}{11.54}} \qquad (2)$$

or [46]

$$\log T=C\cdot(\theta_0-\theta)=M_2-M_1\,\theta \qquad (2a)$$

This equation of Twyman, which states in effect that the logarithm of the relaxation is a linear function of the temperature, is important and will be referred to again.

(*b*) In a theoretical presentation of this general subject, Maxwell [47] suggested as a tentative hypothesis that at a given temperature the rate of disappearance of stress in a strained body is proportional to the stress itself. Twyman states that his experimental results confirm this statement. Tool and Valasek [39] found that the relaxation time increases perceptibly with decrease in the stresses and resulting birefringence. Adams and Williamson [48] deduce from their measurements that the rate of relief of the stress varies, not directly, but as the square of the stress. Expressed in terms of decrease in birefringence this leads to the equation

$$\frac{1}{10^7\cdot\Delta n}-\frac{1}{10^7\cdot\Delta n_0}=T\cdot t \qquad (3)$$

in which Δn_0 is the initial birefringence (stress), Δn the birefringence after the time, t, and T, the relaxation time.

Further experimental evidence will be required to explain these discrepancies, namely: (1) The differences in the rates of change of viscosity as determined by optical and by mechanical methods, respectively, and (2) the rate of relief of stress, as a function of the stress at a constant temperature.

TABLE 9.—*Constants M_1, M_2, C, N of equations 2 and 2a, and annealing temperatures (centigrade) for different times.*

Kind of glass.	M_1 or C	M_2	$\frac{M_2}{M_1}$ or θ_0	N	Time to reduce strain-birefringence from 50.10^{-7} to 5.10^{-7}.							
					1 minute.	5 minutes.	10 minutes.	1 hour.	5 hours.	1 day.	1 week.	1 month.
			°C.		°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.
Borosilicate crown	0.030	18.68	624	10.00	598	575	565	539	515	493	464	444
Ordinary crown	.029	17.33	598	10.31	573	548	538	511	487	464	434	414
Light barium crown	.032	20.10	628	9.41	605	583	574	549	527	506	480	461
Heavy barium crown	.038	24.95	657	7.92	637	619	611	590	572	554	532	516
Barium flint	.028	16.28	582	10.75	555	530	519	491	466	442	412	390
Light flint	.033	15.92	482	9.12	460	439	429	406	385	364	338	320
Medium flint	.038	18.34	483	7.92	463	445	437	416	398	380	358	342
Heavy flint	.037	17.51	473	8.13	453	434	426	405	386	368	345	329
Extra heavy flint	.033	15.03	456	9.12	433	412	403	379	358	337	312	292

[39] Bur. Standards Bull., No. 358, 1920.
[46] Adams and Williamson, Jour. Opt. Soc. America IV, 219, 1920.
[47] Phil. Mag. (4), **34**, 129, 1868.
[48] Jour. Opt. Soc. America, IV, 219, 1920.

In Table 9 [49] are listed the relaxation times required for the reduction of the birefringence from 50×10^{-7} to 5×10^{-7} or, in other words, the path difference per centimeter glass path from 50 millimicrons to 5 millimicrons for different types of glass at different temperatures. The chemical compositions of these glasses are given in Table 11 on page 160. The numbers listed in columns 2, 3, 4, and 5 of Table 9 are the values of the constants $M_1 = C$, $M_2/M_1 = \theta_0$, and N of the foregoing equations 2 and 2*a*. The time required for the relaxation of any given percentage of a stress at a given temperature is stated by the empirical equation (3) in terms of the resulting birefringences. Thus the times required to reduce the birefringences from 500 10^{-7} to 50 10^{-7} and from $50 \cdot 10^{-7}$ to $5 \cdot 10^{-7}$ are in the ratio (equation 3).

$$\frac{\frac{1}{50} - \frac{1}{500}}{\frac{1}{5} - \frac{1}{50}} = \frac{1}{10}$$

From this it is evident that the smaller the stress the longer it takes to relax it. The values listed in Table 9 may therefore be taken as indicating the order of magnitude of the relaxation times for different glasses at different temperatures.

(*c*) Experiments [50] by Peters and Cragoe have shown that the expansion of optical glasses is practically linear up to about 500° C after which the rate increases perceptibly as shown in Table 10 reproduced from their paper. Somewhat above this temperature, moreover, the glass becomes soft and behaves as a strictly viscous liquid. Heat measurements [51] by Tool and Valasek have shown furthermore a perceptible heat absorption in these glasses at this temperature on heating the glass and an evolution of heat on cooling. This heat effect has been ascribed to a change in the molecular groupings within the liquid. Be the cause what it may, there seems to be definite proof of a change in the behavior of the glasses within this temperature range, and in critical work this change must be taken into account.

The first recorded observation on a heat effect of this kind in a glass is that of Day and Allen [52] on borax glass in the heating of which "a slight but persistent absorption of heat appeared in the same region (490°–500° C) and continued over some 20° C, after which the original rate of heating returned."

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[49] Adams and Williamson, Jour. Opt. Soc. America, 4, 219, 1920.

[50] C. G. Peters and C. H. Cragoe, Measurements of the thermal dilatation of glass at high temperatures Jour. Opt. Soc. America, IV, 105–144, 1920.

[51] A. Q. Tool and J. Valasek, Bur. Standards Bull. No. 358, 1920.

[52] The Isomorphism and thermal properties of the feldspars, Carnegie Institution of Washington, Pub. No. 31, p. 34.

TABLE 10.—*Mean coefficient of linear expansion of optical glasses.*

Kind of glass.	Temperature interval °C.	C×10⁴.	Temperature interval °C.	C×10⁴.
Light crown	22–426	0.102	502–522	0.555
Borosilicate crown	22–498	.090	539–562	.393
Barium crown	23–499	.090	589–610	.649
Light flint	22–451	.076	495–511	.292
Medium flint	23–402	.097	452–478	.396
Barium flint	22–494	.088	519–550	.331

(*d*) Measurements of the changes in temperature at different points in a pot of cooling glass have been made by H. S. Roberts [53] by inserting bare base-metal thermoelements (alumel-chromel) into the melt directly after the removal of the pot from the melting furnace. Time-temperature readings were taken for different points within the mass during the entire period of cooling; for each pot of glass a record was also kept of the quality of annealing and of the character of the fracture surfaces. From a series of such data Roberts was able to formulate cooling schedules and methods of treatment of the pot of glass during cooling that insured the kind of fracturing and the quality of annealing desired.

General investigations into the temperature distribution of cooling solids and the stresses arising from changes in temperature gradient have been made by Hopkinson,[54] C. Neumann,[55] Winkelmann and Schott,[56] Lord Rayleigh,[57] Schulz,[58] and more recently by Williamson,[59] and Adams and Williamson,[60] and others.[61] Adams and Williamson have computed tables giving numerical values of several factors involved in the annealing of glass bodies of different shapes and sizes.

We shall now consider the temperature-strain distribution in a pot of cooling glass and shall, for the present, neglect the changes in expansion coefficient just below the softening region of the glass; and assume with Roberts [62] that the coefficient of linear expansion is practically constant throughout the range from room temperature to that at which the glass begins to soften. Glass on heating expands and on cooling contracts; if different parts of the same glass body cool at different rates, these contract at correspondingly different rates and, as a result, internal stresses are produced. The rate at

[53] Jour. Amer. Ceram. Soc., **2**, 543–563, 1919.
[54] Messenger of Mathematics, **8**, 168, 1879.
[55] Theorie der Elasticität, Leipzig, p. 112, 1885.
[56] Ann. d. Phys. **51**, 745, 1894.
[57] Phil. Mag. (6), **1**, 169, 1901.
[58] Sprechsaal, **47**, 460, 478, 1914.
[59] Jour. Wash. Acad. Sci., **9**, 209, 1919.
[60] Physical Rev. N. S. **IV**, 99–114, 1919; Jour. Wash. Acad. Sci., **9**, 609–623, 1919; Jour. Opt. Soc. America, **4**, 213–223, 1920.
[61] Byerly, Fourier Series and spherical Harmonics, Ginn & Co.; Carslaw, Fourier Series and Integrals, Macmillan & Co.; Ingersoll and Zobel, Mathematical Theory of Heat Conduction, Ginn & Co.
[62] Jour. Am. Ceram. Soc., **2**, 546, 1919.

which stresses of this nature are introduced depends on the rate of change, with time, of the temperature gradient, which produces the differences in the rates of contraction. At higher temperatures internal shearing stresses of this kind are relieved by actual flow of the material while at lower temperatures the viscosity becomes so great that such flow is extremely slow and stresses may persist for long periods of time.

At the time of removal of the pot from the melting furnace the temperature throughout the pot is sensibly uniform, as shown by measurements of Roberts. The temperature at this time differs

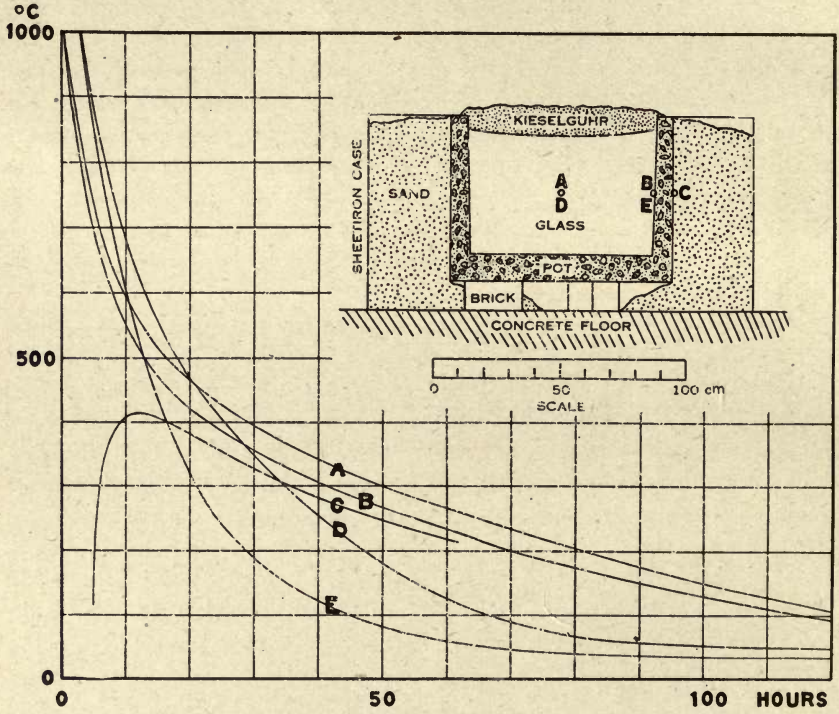

FIG. 43.—Time-temperature curves for melts of optical glass cooled under different conditions. Curves *A*, *B*, *C* are for a melt cooled in sand; curves *D* and *E* for a melt cooled in the open air without any added insulating material.

somewhat for the different types of glasses but ranges between 950° and 1,100° C. On cooling down either in a pot arch or under an insulated casing the temperature of the peripheral portions of the glass melt falls more rapidly than that of the center. The maximum temperature difference is reached generally between 500° C. and 600° C. and may amount to 100° C. or more; but it is commonly less. At 600° C. practically all glasses except dense barium crowns are so soft that any stress arising from a change in the temperature gradient is relieved by flow so rapid that the glass mass remains in an essentially unstrained condition. If it were possible to maintain the tempera-

ture gradient established at 600° C. as an approximately steady state, by linear cooling down to the point at which the outside of the glass mass reaches room temperature, no strain would be introduced by this procedure. But from here on the central portion cools down to room temperature, thereby contracting and tending to pull away from the margins and introducing radial tensional stresses which in turn set up tangential compressive stresses in the peripheral portions of the glass mass. The stresses, thus set up because of the changes in temperature gradient, depend on the temperature difference between the center and the margin of the glass mass and also on its shape, size, and elastic character.

The rates of cooling of the center (curve A) and the side (curve B) of a 36-inch pot of medium flint ($n_D = 1.61$) are shown in figure 43, reproduced from Roberts' paper.[63] Curve *C* shows the rate of

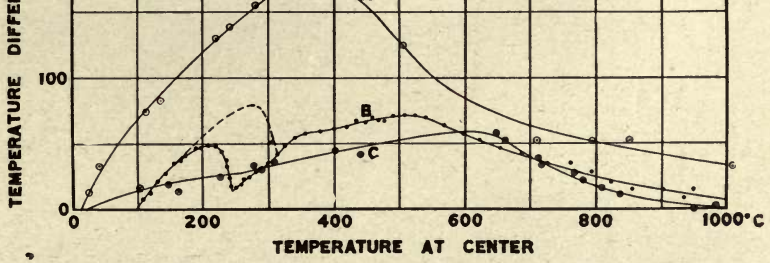

FIG. 44.—Temperature differences between center and margin of melt for different temperatures of the center of three different melts. Curve *A* is for a melt cooled in air without any added insulation; curve *B* for a melt cooled in a pot-arch; curve *C* for a melt cooled in sand.

cooling of the outside of the pot. In figure 44 the differences in temperature between the center and the sides of the glass mass are given for different temperatures (curve *C*). This diagram shows that a maximal difference of about 60° C. is reached at 600° C. and that between 600° and 400° C. the decrease in temperature difference is about 20° C. Curve *A* of figure 43 shows that at 600° C. the melt is cooling at the rate of 17° C. per hour; at 500° C. at the rate of 10° C. per hour; and at 400° C. at the rate of 6° C. per hour. Table 9 of Adams and Williamson, reproduced on page 151, states that at 416° C. the time required to anneal a medium flint is one hour; at higher temperatures the annealing time is much less. The conclusion is therefore justified that at a temperature of 400° C., or slightly above 400° C., the glass mass is free from strain, all stresses resulting from a temperature gradient having been relieved by flow. The measurements by Roberts indicate that with appropriate shift of the temperature limits similar relations obtain for all glasses; and that,

[63] Jour. Am. Ceram. Soc., 2, 559, 1920.

when the glass mass alone is considered without reference to the clay-pot container, the stresses, introduced on further cooling from the softening temperature region down to room temperature, result from the gradual decrease of the temperature gradient between the center and the margins; in other words, from this temperature region down to room temperature the center of the glass mass is cooling faster than the periphery. Radial tensional stresses arise as a result of this change in temperature and tend to produce spherical cracks and shells not unlike, in general appearance, the concentric outer shells of an onion. This type of fracture is designated "exfoliation" in geology and is of common occurrence in the field.

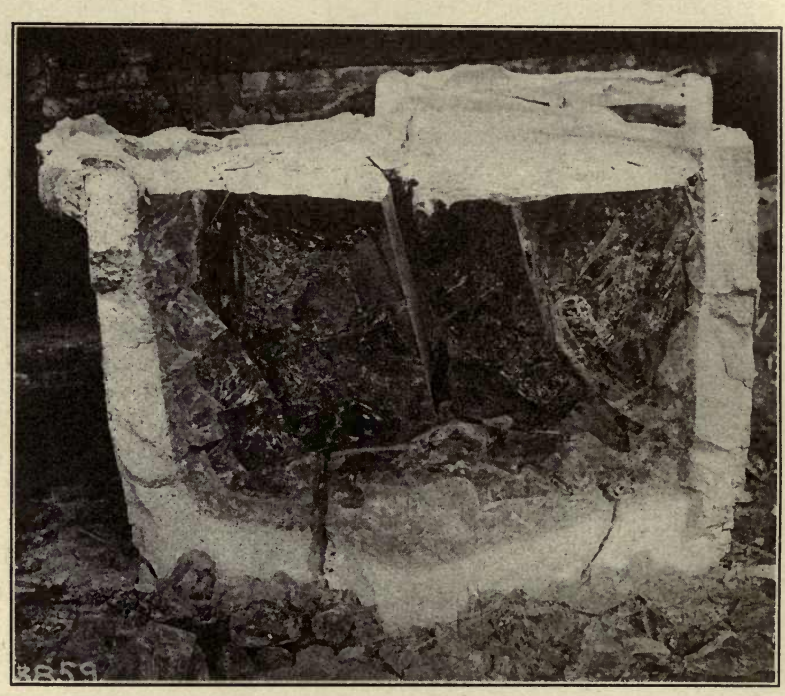

FIG. 45.—Well annealed melt showing plane cracks. (Photograph by H. S. Roberts at the Charleroi plant of the Pittsburgh Plate Glass Co.)

It is possible to increase temporarily the temperature difference between the center and the margins by chilling the margins. In this case the outside is chilling at a faster rate than the center and, as a result, stresses of radial compression and tangential tension in the outer shells are introduced, which tend to cause the glass mass to crack or split along radial planes normal to the boundary surfaces, whereas, in the case of the decreasing thermal gradient, cracks parallel with the boundary surfaces tend to be produced.

A cooling glass melt is similar in many respects to cooling lava. A lava flow, after it has cooled to the temperature of its surroundings,

is seen to be filled with cracks and fissures running approximately parallel and normal to its surface. These cracks develop as a result of the contraction of the cooling lava and are a characteristic phenomenon not only in lavas but also in intrusive igneous rocks and in sedimentary rocks. Similar cracks occur, as mud cracks, in clay or argillaceous material on drying out. Cracks and jointing phenomena of this nature are so well known that further description is unnecessary. Suffice it to state the glassmaker desires to find each pot of glass, when cold, cracked into large rectangular, well-annealed blocks bounded by relatively plane and smooth surfaces. (Fig. 45.) Under unfavorable or improper rates of cooling, fissuring and jointing of this

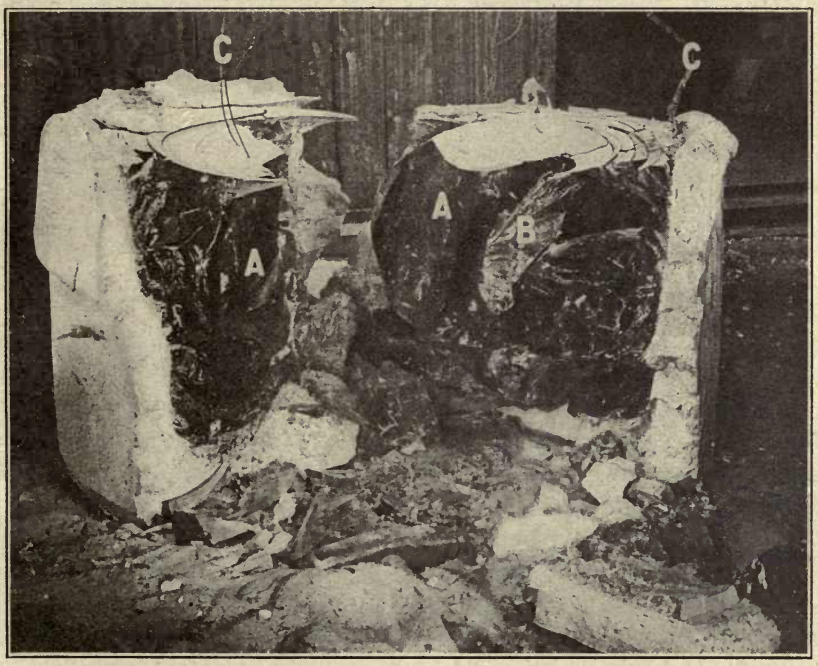

FIG. 46.—Poorly annealed melt showing spherical cracks. (Photograph by H. S. Roberts at the Charleroi plant of the Pittsburgh Plate Glass. Co.)

kind does not develop, but spherical cracks abound and shells of the glass mass are found split off and away from a compact, rounded central core. (Fig. 46.) Large "marbles" or "onions" of this type are unwelcome, because they do not split regularly, but into sharp, irregular, and wedge-shaped chunks, with the result that much glass is lost. The glass which is obtained is, moreover, in fragments unsatisfactory for molding or pressing; its fracture surfaces are rough and so uneven that the glass can not be satisfactorily inspected. In the properly cooled melt the spherical cracks (analogous to the exfoliation cracks in rocks) do not affect a large amount of glass. The body of the glass is fissured by vertical and occasional horizontal

plane cracks, through which the quality of the glass can be readily seen, as through a polished plane surface. The modes of formation of these radial, plane fissures as contrasted with the concentric spherical cracks (exfoliation) are evidently different and require explanation. In this connection the following facts are significant:

The temperature measurements of Roberts cited above prove that, in general, the maximum temperature difference between the center and the margins of a pot of molten glass on cooling from 1,100° or 1,000° C. is reached at approximately 600° C.; at this temperature, all shearing stresses arising from the changes in the temperature gradient are eliminated by actual flow of the viscous glass. From this temperature region down to room temperature, the temperature difference between the center and the margins gradually decreases; the center cools more rapidly than the margins and in consequence tends to contract and to pull away, thereby setting up tensional radial stresses. Analysis of the stresses produced in a glass mass cooling under these conditions [64] proves that the radial tensional stresses in a cylinder or a sphere increase from zero at the periphery to the maximum value at the center while the accompanying tangential stresses are compressive at the margins, gradually decrease toward the center, become zero, and then increase as tensional stresses attaining a maximal value equal to the radial stress at the center.

In a body cooling under these conditions, the tangential stresses at the margins are compressive and therefore unfavorable to the formation of radial cracks. Some other cause must be sought to account for the observed type of fracture.

It was noted during the early months of the war that a change in the make of a pot (change in materials and in thickness of pot walls) resulted in unfavorably fractured pots of glass; this was remedied by a change in the cooling schedule. Experience taught that in general an average cooling rate of 8° C. or less per hour from 600° to 350° C. resulted in satisfactorily fractured and annealed glass whereas cooling at double this rate or 15° C. per hour resulted in poorly annealed and exfoliated "bowlders" or "marbles" of glass. A further proof of the influence of the pot on the character of the fracture of the glass was furnished later by H. S. Roberts, who reheated a "marble" very slowly by insulating it well in sand and then cooled it somewhat more slowly than the cooling rate of the ordinary pot. The result was a well-annealed block without cracks, thus indicating the influence of the pot in producing cracks in the glass mass cooled under these conditions.

The coefficient of linear expansion of the material of optical glass pots varies with the ingredients of the pot. As an average we may assume its coefficient of linear expansion to be about $50 \cdot 10^{-7}$. The

[64] E. D. Williamson, Jour. Wash. Acad. Sci. 9, 209–217, 1919.

coefficients of linear expansion of optical glasses range from about $60 \cdot 10^{-7}$ to $100 \cdot 10^{-7}$.[65] Thus it is $97 \cdot 10^{-7}$ for a medium flint glass (Table 10, page 153).

The significant fact is that in all cases the pot walls contract less on cooling than does the glass adhering to them, with the result that the glass is put under elastic tension, whose magnitude depends on the difference in expansion coefficients between the glass and the containing pot.

The stresses which arise as a result of these relations can be computed on the assumption that the pot of glass is cylindrical in shape and that for diametral plane sections near the center of the pot a plane normal to the axis of the cylinder remains a plane throughout the contraction. The stresses, which arise as a result of linear cooling at such a rate that a difference in temperature between the center and the periphery of 100° C. is attained in the steady state, are for a pot of medium flint glass of radius, $r = 40$ centimeters (diameter of pot about 30 inches) in kilograms per square centimeter:[66]

$$\text{(Radial)}\quad P_2 = \frac{\alpha\, h(a^2 - r^2)}{16\kappa\ (e-f)}$$

$$\text{(Tangential)}\quad P_3 = \frac{\alpha\, h(a^2 - 3r^2)}{16\kappa\ (e-f)}$$

in these equations P_2 and P_3 are the radial and tangential stresses, respectively, at the point r; $\alpha = 97 \cdot 10^{-7}$ is the expansion coefficient for medium flint; $h = 0.001$°C., temperature increase or decrease per second to maintain a constant difference of 100° C. between center and margin of glass cylinder 80 centimeters in diameter; $\kappa = 0.004$, the diffusivity; $e = \frac{3K+R}{9RK}$ and $f = \frac{3K-2R}{18RK}$ are elastic constants, e being the elongation of glass rod or bar of unit length and area caused by a load of 1 kilogram, and f the accompanying contraction in the direction normal to the direction of the load and axis of the rod; Young's modulus is $1/e$ and Poisson's ratio, f/e; the constants K and R are, respectively, the modulus of compressibility (bulk modulus) and the modulus of rigidity. Values of the elastic constants for different glass types are listed in Table 11 of Adams and Williamson[67]; in this table the weight percentage chemical compositions, and data on birefringence, on thermal diffusivity, and on linear expansion are also listed.

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[65] Peters and Cragoe, Jour. Opt. Soc. America, **IV**, 105–144, 1920.

[66] E. D. Williamson, Jour. Wash. Acad. Sci., **9**, 216, 1919.

[67] Jour. Wash. Acad. Sci., **9**, 613, 1919; Jour. Franklin Institute, **190**, 607, 1920.

TABLE 11.—*Chemical and physical constants of different types of optical glasses.*

Kind of glass.	Chemical composition (approx.) wt. per cent.								
	SiO_2.	Al_2O_3.	B_2O_3.	PbO.	ZnO.	BaO.	CaO.	K_2O.	Na_2O.
Borosilicate crown	67	.....	12	.....	.....	4	.....	8	9
Ordinary crown	73	.....	.....	.....	.....	.....	12	1	14
Light barium crown	47	1	4	.....	11	29	.....	5	3
Dense barium crown	40	3	6	.....	8	43	.....	.....	.....
Barium flint	46	.....	.....	24	8	15	.....	4	3
Light flint	54	.....	.....	35	.....	.....	.....	5	6
Medium flint	45	.....	.....	48	.....	.....	.....	4	3
Dense flint	42	.....	.....	52	.....	.....	.....	3	3
Extradense flint	28	.....	.....	69	.....	.....	.....	3	.....

Kind of glass.	Optical properties.			Mechanical properties.		Thermal properties.	
	Refr. Index n_D.	ν	Bi-efringence due to 1 kg/cm² load. B	Modulus of compressibility kg/cm². K	Modulus of rigidity kg/cm². R	Coeff. of linear expansion. α	Thermal diffusivity. cm²/sec. κ
Borosilicate crown	1.516	62	-2.85×10^{-7}	0.43×10^{6}	0.29×10^{6}	7.5×10^{-6}	0.0045
Ordinary crown	1.523	59	-2.57×10^{-7}	0.46×10^{6}	0.28×10^{6}	8.9×10^{-6}	0.0047
Light barium crown	1.574	57	-2.81×10^{-7}	0.52×10^{6}	0.30×10^{6}	7.4×10^{-6}	0.0039
Dense barium crown	1.608	57	-2.15×10^{-7}	0.53×10^{6}	0.29×10^{6}	6.4×10^{-6}	0.0040
Barium flint	1.606	44	-3.10×10^{-7}	0.42×10^{6}	0.26×10^{6}	7.7×10^{-6}	0.0038
Light flint	1.573	42	-3.20×10^{-7}	0.35×10^{6}	0.24×10^{6}	8.4×10^{-6}	0.0040
Medium flint	1.616	37	-3.13×10^{-7}	0.34×10^{6}	0.22×10^{6}	8.1×10^{-6}	0.0038
Dense flint	1.655	33	-2.67×10^{-7}	0.34×10^{6}	0.22×10^{6}	8.2×10^{-6}	0.0036
Extradense flint	1.756	27	-1.22×10^{-7}	0.32×10^{6}	0.20×10^{6}	8.5×10^{-6}	0.0033

Substituting the appropriate values for the medium flint in the above equation, we find for the marginal shell ($r = a$) the stresses $P_2 = 0$

$$P_3 = -\frac{97\cdot10^{-7}\times0.001\times1600\times2}{16\times0.004\times(1.842\cdot10^{-6}-0.431\cdot10^{-6})} = -343.72 \text{ kg. cm}^2.$$

For a rate of linear heating $h = 0.005$ per second, the tangential compressive stress [68] is 171.86 kg. cm². The stresses at the center ($r = 0$) are

$$P_2 = P_3 = \frac{\alpha h a^2}{16\kappa(e-f)} = \frac{97\cdot10^{-7}\times0.001\times1600}{16\times0.004\times1.411\cdot10^{-6}} = 171.86 \text{ kg. cm}^2.$$

Both stresses are tensional.

The flint glass mass at a temperature 400° C. or higher is practically without strain in spite of the temperature gradient existing at that temperature. On cooling the temperature gradient gradually disappears, but in so doing gives rise to stresses which persist except for that part of the stresses which is eliminated by viscous flow. As a first approximation we may consider the above stresses, tangential and radial, computed for the margin and center of the mass as representative of the order of magnitude of the actual stresses existing in the glass mass at room temperature.

[68] Tensional stresses are considered positive, compressive stresses negative.

As a result of the difference in coefficients of expansion of the glass mass and of the containing pot to whose walls the glass adheres, elastic tensional stresses are set up and superimposed on the stresses induced by the disappearance of the temperature gradient. These stresses can be computed if, as before, we assume the pot to be cylindrical in shape and consider only central diamentral planes located at a distance from the ends. The total linear contraction of the glass per unit length from 420° to 20° C. is then $400 \cdot 97 \cdot 10^{-7}$; the total linear contraction of the pot is $400 \cdot 50 \cdot 10^{-7}$; and the difference in elongation is $400 \cdot 47 \cdot 10^{-7} = 0.00188$. If the pot walls were perfectly rigid the linear stretching per unit length of the adhering glass mass would be 0.00188, but as this is not the case, we may, as a first approximation, assume that the walls are pulled in as much as the glass is stretched out, in which case the elongation per unit length in the glass mass is 0.00094. Let P_1, P_2, and P_3 be the axial, radial, and tangential stresses, respectively, at a given point. The equations for the elongations E, F, and G in the directions P_1, P_2, and P_3 are then

$$E = eP_1 - fP_2 - fP_3$$
$$F = -fP_1 + eP_2 - fP_3$$
$$G = -fP_1 - fP_2 + eP_3$$

But, under the assumptions made, $P_1 = O$ and $P_2 = P_3$. Therefore

$$P_2 = P_3 = \frac{0.00094}{e-f} = \frac{0.00094}{1.411 \times 10^{-6}} = 665.19 \text{ kg. cm}^2.$$

Under these conditions there are superimposed on the glass mass, as a result of the interaction between pot and glass on cooling, tensile stresses both radial and tangential which approach the elastic limit of the glass in magnitude. The radial tension on the marginal layer of glass is then 665 kg. cm²; the tangential tension is $665 - 344 = 321$ kg. cm.² for the larger temperature difference and 493 kg. cm² for the smaller temperature interval ($h = 0.0005°$ per sec.) Both the tangential and the radial tensional stresses increase from the periphery to the center; at the center their order of magnitude is $665 + 172 = 837$ kg. cm.² The tensional stresses at the center are hydrostatic.

The foregoing values are only first approximations; but they indicate that in the glass mass itself tensional stresses of considerable magnitude are present such that, if a mechanically weak point were to develop in the glass, the system is mechanically unstable and so near failure that cracks of considerable magnitude would probably develop. The pot walls are for the most part, moreover, under heavy tangential compression and show little tendency to crack radially.

In case the pot of glass were to cool more rapidly than usual so that for example $h = 0.002°$ per second, then $P_3 = -687.44$ kg. cm.^{2} Under these conditions the final tangential stress in the marginal layer is still compressive $665 - 687 = -22$ kg. cm.^{2} and there is no tendency for radial cracks to form. Under these conditions of rapid cooling the glass is not only poorly annealed, but is not cracked transversely, and a "marble" or "onion" is the result.

It is a matter of factory observation that the pot walls at the margins of a cold pot of glass are cracked but little, and that it is in many cases difficult to find a pronounced crack on the outside of the pot without examination of the glass itself.

The foregoing explanation of the formation of cracks is not complete and does not account adequately for the fact that in a properly cracked pot of glass a master vertical plane fissure divides the part into halves. The formation of the other joint cracks, roughly perpendicular to the master joint-plane, is readily deduced from symmetry relations and the existing tensional shearing stresses.

Roberts[69] found that rapid chilling of the pot of glass at about 300° C., induced by removal of the insulation, or by turning off the gas and opening the dampers in the case of melts cooled in the pot arch, favored the formation of radial cracks. Tangential tensional forces are introduced by this procedure, and the general cooling schedule of the glass is thereby disturbed so that a mechanically weak spot might give way and thus introduce the radial cracks. Once radial cracks have begun to appear the tendency for the spherical cracks to form is diminished.

It may be noted that the plane cracks (joints), produced as described above, form slowly and with reference to the distribution of the shearing stresses involved; in other words they form with reference to the symmetry of the pot. Similar phenomena are of common occurrence in nature as, for example the columnar jointing of certain lava flows in which the joint columns are normal to the cooling boundary surfaces. For the formation of plane joint cracks, slow and fairly uniform cooling is essential. In the case of stresses developed by the sharp blow of a hammer, the distribution of the elastic stresses is entirely different, and characteristic wavy or conchoidal fracture surfaces develop in well-annealed glass or other homogeneous material. If, however, there exist other stresses, as in a block of poorly annealed, badly strained glass, in addition to those developed momentarily by mechanical means, the fracture surface resulting from the hammer blow is uneven and commonly hackly in nature; it is rough and torn as though the glass had been split across some internal structural lines, as in a block of wood.

[69] Jour. Amer. Ceram. Soc., 2, 543–563, 1919.

There is a noticeable difference between the types of fracture developed in a mass of glass or other homogeneous material on cooling and on that produced on heating. As a rule the cooling cracks tend to be plane surfaces intersecting at angles ranging between 60° and 90° and to be approximately normal to, and parallel with, the bound ary surfaces. Cracks developed on rapid heating are commonly warped surfaces, rarely plane and rarely showing any tendency toward regularity in the mode of their intersections. This criterion was successfully applied during the war to detect and to locate sabotage by enemy aliens in the grinding and polishing department of one of the plants devoted to the manufacture of optical munitions.

POT-ARCH COOLING.

During the war different methods of cooling the melt were employed and served the purpose well. During 1917 the method first described by Schott in 1888 [70] was followed; it had been in use at the Bausch & Lomb plant before our arrival. The pot after removal from the furnace was allowed to stand in the open air on fire-clay supports and to cool for a period of 15 to 45 minutes. It was then placed on similar fire-clay supports in the heated pot arch from which the new empty pot had just been removed and set in the melting furnace. During the interval occupied with the exchange of pots the door of the pot arch was left open and its heating chamber allowed to cool to 700° or 800° C. The pot arch was then closed, its burners lighted and the pot temperature allowed to fall to a dull-red heat (500° to 600° C.) in about 20 hours, after which the burners and stack drafts were either closed completely and the pot arch was sealed, or the burners were turned gradually lower so that by the end of the next day (24 hours) the temperature had fallen to about 350° C. It was found by measurement of the pot-arch temperatures that if the cooling rate between 600° and 350° C. averages 8° C. drop per hour satisfactory annealing and transverse fissuring result; but if the temperature falls at a rate of 12° to 15° C. per hour poor annealing and a poor quality of fracturing are obtained. Between 350° to 300° C. the burners are turned off and the furnace is allowed to cool at a normal rate. By this time the transverse fissuring has probably begun. Cold-air drafts should be avoided in the pot arch, as these may supercool the glass pot locally and thereby induce local irregularities.

At the Spencer Lens plant C. N. Fenner modified this schedule somewhat. He found that satisfactory annealing and fracturing results if the pot of molten glass after removal from the melting furnace and an exposure of about 15 minutes to the open air is placed

[70] Ueber Glasschmelzerei für optische und andere wissensch. Zwecke. Verein zur Beförderung des Gewerbefleisses, 4 June, 1888.

in the heated pot arch and the burners are so adjusted that the temperature drops to a dull-red heat (500° to 600° C.) in about 16 hours. The burners are then either turned off completely and the pot arch is sealed so that its heat is lost solely by conduction through the furnace walls, or the burners are so adjusted that the pot-arch temperature above the pot drops to 400° C. in about 24 hours. After this the burners are turned off and the pot arch is allowed to cool.

At the Pittsburgh Plate Glass Co. the pot-arch method used by Roberts [71] was not greatly different from the foregoing. The melt was cooled fairly rapidly (in 20 hours) to about 500° C., but still

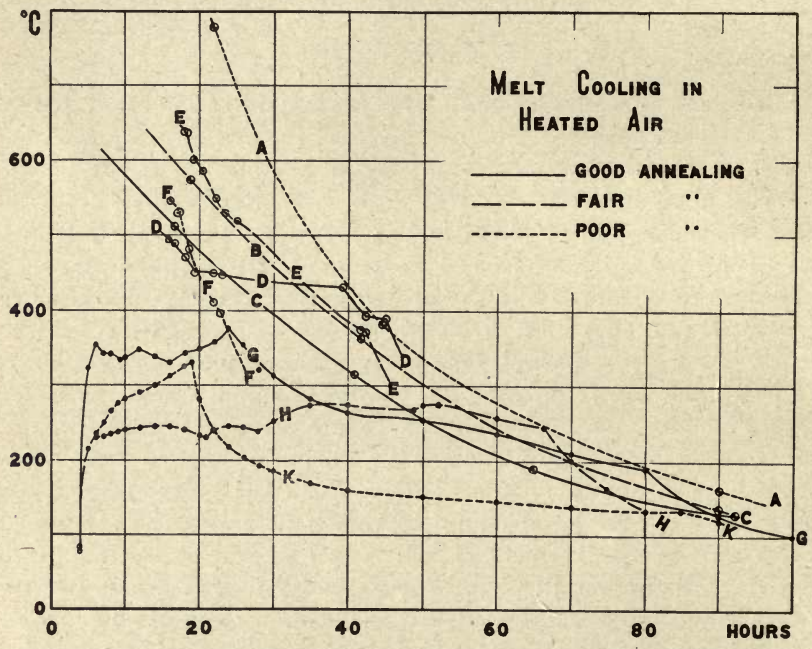


FIG. 47.—Time-temperature curves for optical glass melts cooled in a pot arch. The temperatures are those of the air over and close to the pot. The quality of the annealing and fracture in each case are indicated by the symbols chosen to represent the curve.

sufficiently slowly that the temperature difference between the center and the sides of the glass mass did not exceed 75° C. The melt cooled from 500° C. to 300° C. in the next 30 hours when the heat was turned off, the rate of cooling of the pot being thereby temporarily accelerated. In all cases Roberts insulated the top surface by a layer, 3 to 4 inches thick, of diatomaceous earth.

The results of the three different methods of cooling are summarized in figure 47 reproduced from Roberts article.[72] These curves show that slow cooling through the high temperature range serves no purpose; whereas slow cooling through the annealing range from

[71] Jour. Am. Ceram. Soc., 2, 553, 1919.
[72] Jour. Amer. Ceram. Soc., 2, 556, 1919.

500° to 300° C., is essential to successful annealing and to transverse fracturing of the glass mass.

INSULATION TO REGULATE RATE OF COOLING.

Because of the fact that the temperature range, through which careful regulation of the rate of cooling is required, is below 600° C., it is possible to envelop the pot of molten glass with heat-insulating material and thus to retard its cooling rate as effectively as in a pot arch. This method of pot cooling was developed chiefly at the Pittsburgh Plate Glass Co. and was placed on an effective routine basis by Mr. H. S. Roberts. Either sand or a better heat-insulating material, such as diatomaceous earth (kieselguhr), may be used and the pot surrounded by it. A layer of sand 8 inches thick suffices for pots 30 to 50 inches in diameter. The moving of the sand is a laborious operation and the final form of insulating device, as developed both at the Pittsburgh Plate Glass Co. and at the Bausch & Lomb Optical Co., was essentially a hollow, double-walled, sheet-iron cap in the form of a cylinder closed at one end and equipped with handles for lifting. The space, 3 to 4 inches wide, between the walls and the ends of this cap are filled with light, diatomaceous earth. A drum of this design is easily handled and, when placed in position over the cooling pot, provides adequate heat insulation. The schedule followed by Roberts for this method is briefly: On removal of the pot of molten glass from the melting furnace place it on three fire-clay blocks at least 8 inches high to allow adequate circulation of air along base of pot. Cover surface of melt with a layer 3 to 4 inches thick of diatomaceous earth. Four hours later for 36-inch pots and eight hours later for 49-inch pots apply insulation in the form either of an 8-inch layer of loose sand or of the sheet-iron insulating cap. In all cases shovel loose sand or kieselguhr as insulation beneath pot. Remove insulation from 36-inch pot three days later and from 49-inch pot five days later. Pot can be broken up two or three days later. The temperatures at the different stages of this operation were measured by Roberts and are listed in Table 12 reproduced from Roberts article.[73]

TABLE 12.—*Approximate temperatures at center of 36-inch pot melts cooled in sand.*

Type of glass.	n_D.	Temperature set out.	Temperature after 4 hours.	Annealing temperature.	Temperature after 72 hours.
		° C.	° C.	° C.	° C.
Light flint	1.57	1,038	800	465	320
Medium flint	1.61	996	780	455	300
Dense flint	1.66	968	760	445	290
Ordinary crown	1.52	1,093	850	570	350
Borosilicate crown	1.52	1,116	860	590	360
Light barium crown	1.57	1,016	790	580	310
Dense barium crown	1.61	1,016	790	600	310

[73] Jour. Am. Ceram. Soc., 2, 561, 1919.

BREAKING UP A POT OF GLASS.

The pot of glass, after having cooled to room temperature, is set out on the floor of the furnace hall where it is broken apart. (Fig. 48.) In this operation care is taken to preserve intact the large blocks of glass bounded by joint planes. Commonly a vertical master joint divides the pot into halves; the pot is split along this plane by means of the chisel edge of a crow bar; the blocks of glass are then jarred loose from the pot by tapping it with a sledge hammer. The glass blocks are not hit directly with the hammer because of the

FIG. 48.—Breaking apart pots of optical glass. Note the sheet-iron insulating cap on left, also storage box for pot of optical glass on right of photograph. (Photograph by J. Harper Snapp at plant of Bausch & Lomb Optical Co.)

shattering and loss which would be thereby incurred. All pot fragments are separated from the glass and the entire mass of raw glass is transferred to a box of standard size and divided into several compartments to hold the small and large pieces of glass. (Fig. 48.) Labels are attached to each box giving the number and date of the melt and the type of glass. The boxes are made with raised bottoms, so that a special lifting truck can be used to move them from place to place as needed without tilting. Boxes of this kind, made of heavy lumber and of standard shape and adequate size are convenient; they can be stored three or four deep and were found to be satisfactory in every respect. It is essential that each pot of glass be treated as a unit in subsequent operations, otherwise there is danger of mixing one type of glass with another and this leads

to disastrous results in later factory routine. Meticulous care should be exercised to avoid mixing different glass melts.

Before transferring the box of raw glass to the storage vault, it is examined while still on the floor of the furnace hall by means of a strong electric light [74] for striae, stones, color, bubbles and seeds, character of fracture, size of blocks, and state of annealing; a rough estimate is made of the general quality and percentage yield of usable glass in the melt. A record of this preliminary inspection, together with the optical constants measured on pieces, selected at random from the broken fragments is filed for reference and enables the manager to form an estimate of the kinds and quality of raw glass on hand and available for further operations.

The box of glass is now transferred from the furnace hall to the storage vault and passes out of the hands of the glassmaker to the trimmers and thence through the pressing and molding stages to the grinders and polishers, to the inspectors and thence back to the storage vault. These stages of the manufacturing process will now be considered briefly. Before leaving the furnace hall, however, a modification of the standard process of optical glass manufacture may be discussed because it was introduced during the war as a time-saving method and proved in practice to be well adapted for certain purposes.

CASTING OF OPTICAL GLASS.

Spectacle lenses are made from ordinary crown glass rolled into sheets similar to plate glass. This process of manufacture is distinctly different from that of optical glass and has many advantages in its favor. The casting process, as practiced in the plate-glass industry, is briefly the following: The pot of molten glass, after it has fined properly and cooled somewhat, is removed from the melting furnace and lifted by a traveling crane to a heated, flat, iron casting table, 14 feet wide and 22 feet long, on which the molten glass is poured and then rolled out into a sheet of the desired thickness by means of a heavy cylindrical iron drum 20 inches in diameter. The sheet of glass is then pushed into a heated annealing oven or lehr where it cools down to room temperature in the course of a day or so, depending on the thickness of the sheet. The empty melting pot is returned at once to the melting furnace and is gradually refilled with raw batch for a new run. Casting pots may be used for 10, 20, and even 30 or more runs. The quality of glass has been found to improve after the first two or three runs because the walls of the pot become more tightly sintered and baked, and offer greater resistance to the metal.

[74] A portable automobile head or search light answers the purpose well.

This procedure eliminates many of the troublesome operations connected with the cooling-down process, and also with the molding and pressing, annealing and grinding, and polishing of the blocks of pot glass preparatory to the final inspection. During the rolling operation the striae in the molten glass are spread out as thin sheets and bands or ribbons parallel with the surfaces of the plate and hence do not appear when the plate, after polishing, is examined through the "flats," as for instance in a window pane of plate glass. If, however, the plate is examined through the edges, it resembles a pile or ream of sheets of paper viewed edgewise; hence the plate-glass maker's name, "ream," for this kind of striae. Striae arranged uni-

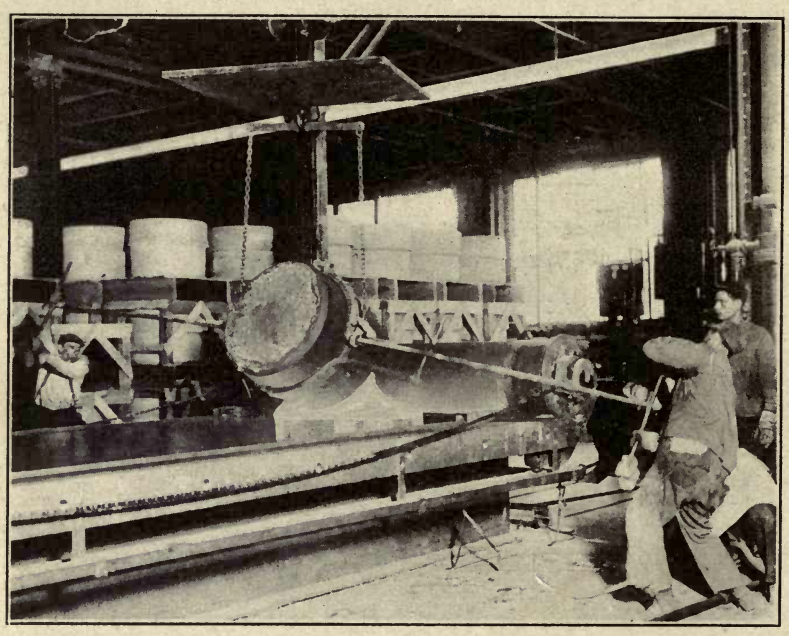


FIG. 49.—Casting a small pot of light crown optical glass. (Photograph by J. Harper Snapp at plant of Bausch & Lomb Optical Co.)

formly in this manner are readily detected when the glass plates are examined through the fracture surfaces obtained on cutting a sheet of glass into small plates by means of a diamond point or glass-cutter's wheel.

Were it possible to produce optical glass of good quality by this method much time and expense would be saved and production expedited materially. Before the war rolled spectacle crown glass had been successfully used for certain lens elements, such as eyepiece field lenses, graduated scales (reticules), and prism shields in certain fire-control instruments. Experiments were accordingly tried both at the Pittsburgh Plate Glass Co. and at the Bausch & Lomb Optical Co. to pour and to roll optical glass after the manner of plate glass.

The pot of optical glass is removed from the furnace at a temperature at which the melt is still fairly liquid or fluent and is transferred as quickly as possible to the casting table. Experience is required to pour glass properly, and for the purpose the services of an experienced hand at casting plate glass are valuable. (Fig. 49.) The temperatures at which 49-inch pots should be removed from the furnace for casting are, for the different types of glass, the temperatures at which in the stirring operation it is necessary to reduce the size of the stirring circle and are approximately[75] the temperatures listed in Table 13.

TABLE 13.—*Casting temperatures for different types of optical glass.*

Type of glass.	n_D.	Temperature of melt on removal from furnace for casting purposes.	Type of glass.	n_D.	Temperature of melt on removal from furnace for casting purposes.
		° C.			° C.
Ordinary crown	1.52	1,200	Light flint	1.575	1,160
Borosilicate crown	1.515	1,200	Medium flint	1.615	1,140
Barium crown	1.57	1,175	Dense flint	1.65	1,100
do	1.61	1,200	Barium flint	1.61	1,175

The results obtained with rolled optical glass prove that it is possible with careful selection to produce optical glass of good quality by this method. For most lens elements rolled optical glass is satisfactory, because in these lenses the light passes approximately normal to whatever ream may be present. Striae and ream are present in sheets of glass rolled from well-stirred melts, because even in these melts it is impossible to eliminate entirely the differences in composition between the margins and the center of the melt resulting from pot solution and from selective volatilization of the melt. These peripheral portions are spread through the homogenous central portion of the melt by the rolling operation and give rise locally to "ream."

Experience with rolled optical glass has proved definitely that the casting method is not only feasible but, in many respects, superior to the ordinary method, especially as a war-time measure. It is an entirely American development and its adoption during the war resulted in an appreciably increased rate of production. For large prisms, especially pentaprisms and roof-angled prisms in which the light rays traverse the prism in different directions, glass practically free from striae is required and is best obtained by the standard method of manufacture. But for ordinary, low-power visual instruments and

[75] Taken in part from Hostetter and Roberts, Jour. Am. Ceram. Soc., 3, 1920.

photographic lenses the quality obtained by pouring and rolling is satisfactory.

All types of glass may be cast if certain precautions are observed. The flint series, and even extra dense flints, are of course most readily cast because of their viscosity relations and ease of annealing. Sheets of glass 2 inches thick may be cast by experienced hands under properly regulated conditions.

For many purposes inspection through the edges of the small plates cut with a diamond from a large sheet suffices for the detection of imperfections, such as striae, bubbles, stones, strain, and color. For more critical work the edges should be ground and polished so that rectangular plates are obtained. Inspection of plates of rolled glass polished on the sides only (flats) may fail to reveal the presence of heavy ream.

FIG. 50.—The inspection of optical glass in rough chunks. (Photograph by J. Harper Snapp at plant of Bausch & Lomb Optical Co.)

PREPARATION OF RAW POT GLASS FOR PRESSING OR MOLDING.

The operations described in this and the next few sections apply only to raw pot glass and not to rolled optical glass. From a production standpoint one of the advantages of rolled optical glass over ordinary optical glass is the reduction of the number of factory operations required to produce the rolled stock and the consequent saving of time and expense which result therefrom.

Each pot of raw pot glass as it is received from the storage vault or from the furnace hall is inspected in the rough (fig. 50) and the portions of each block which contain striæ or other imperfections are trimmed off. The large blocks are broken into smaller pieces suitable for molding and pressing. For this purpose a heavy hammer and a sharp chisel with a cutting edge 1 to 2 inches long are used. (Fig. 51.) The block of glass is placed on several thicknesses of thick, compact felt which shields the glass from bruises; the block is struck a sharp quick blow. With practice the operator can break a block of glass into nearly rectangular pieces with approximately flat sides. To

accomplish this, well annealed glass is essential; poorly annealed glass breaks so irregularly and with such rough surfaces that it is exceedingly difficult to prepare smooth pieces from it.

For the direct inspection of the glass blocks a source of illumination interrupted by dark areas is advisable; thus skylight entering through a window of many small panes or through a wide lattice work placed in front of a large window pane is better than uninterrupted skylight, because faint imperfections, such as fine striæ, can be

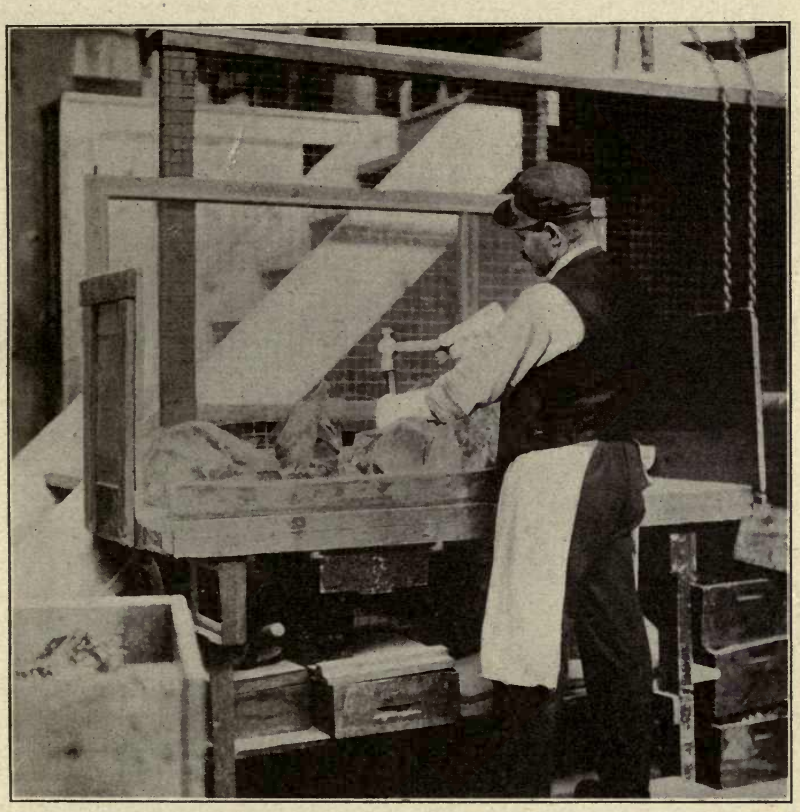


FIG. 51.—Trimming raw optical glass. (Photograph by J. Harper Snapp at plant of Bausch & Lomb Optical Co.)

seen more readily in half-shadow, oblique illumination than in direct illumination. The pieces containing imperfections are discarded as cullet; the pieces free from obvious imperfections are trimmed preparatory to the pressing or molding operations. Reentrant angles are broken off; bruises and blemishes from the chisel are trimmed off; irregular and sharp angles are ground off. The glass blocks are best trimmed by the use of tough steel chipping-blocks; these are essentially square pieces of hard steel, one-fourth to one-half inch thick and 3 or more inches on a side, clamped upright by a screw bolt into a heavy iron

support. (Fig. 52.) The edges of the plate are ground sharp; the piece of glass to be trimmed is placed against the edge or corner of the steel plate and the glass block is struck a blow on the opposite side with a weighted but light hammer of fiber, leather or celluloid. A hammer of this kind does not bruise the glass and enables the trimmer to chip off pieces of glass of almost any size and shape from the block. With a little practice trimmers become expert and prepare pieces of glass for pressing in a short time. Unless closely supervised, however, they may become careless and waste a considerable amount

FIG. 52.—Trimming defects from pressed plates of optical glass. (Photograph by J. Harper Snapp at plant of Spencer Lens Co.)

of good glass. The trimming tables are brushed off and cleaned thoroughly after the preparation of each pot of glass in order that glass from different pots may not be mixed.

THE INSPECTION OF RAW GLASS BY THE IMMERSION METHOD.

For the careful inspection of optical glass it is necessary that the surface imperfections be removed either by grinding and polishing plane-parallel surfaces or by immersing the glass fragment in a liquid of the same refractive index. The latter method was suggested and tried out by the writer in May, 1917 (Weekly Report No. 3 for week ending May 19, 1917), but was not adopted as a factory method

because of the difficulty of obtaining suitable refractive liquids. Half a year later the method was tried and adopted at the Pittsburgh Plate Glass Co. A mixture of carbonbisulphide and benzol was used, in spite of the danger from fire and of the possibility of distress to the workman caused by the carbonbisulphide fumes.

Faint striae in optical glass are detected because their refringence is slightly different from that of the surrounding glass. Two methods are in common use to render faint striae visible; both depend on the deviations, produced by the striae, in the paths of transmitted light rays; these in turn give rise to differences in intensity of field illumination which under favorable conditions can be readily seen. Appropriate methods for this purpose are described in detail in the next chapter. A simple method for rendering striae visible in a block of glass immersed in a liquid of the same refringence is to examine the block against a background 6 feet away, consisting of a lattice work or a sheet iron plate, in which a series of rows of half-inch holes have been drilled, placed directly in front of a frosted or opal sheet of glass illuminated from behind by an electric light. In the half shadows of the field illuminated in this manner striae stand out distinctly as faint shadows or lines of light.

A second, more sensitive method was also used at Pittsburgh and was developed especially by Mr. W. H. Taylor, of the Bureau of Standards. In place of white light, monochromatic light obtained by prismatic refraction (carbonbisulphide dispersion prism with collimator and telescope) was used; it enabled the observer, by proper shift of the spectral color, to obtain a very accurate match in refractive index between the liquid and the immersed block, thus causing the surface markings of the block to disappear altogether and hence rendering the field illumination uniform in the case of glass free from striae. Lenses are used in this method to render the transmitted rays parallel and thus to increase its sensitiveness.

The refractive liquid tank, as developed at the plant of the Pittsburgh Plate Glass Co., is made of a piece of iron plate one-eighth to one-fourth inch thick and bent into a flat-bottom U-shape; this forms the bottom and two of the sides of the tank. The two remaining parallel sides are of plate glass cemented to the iron plate by a mixture of glue and plaster of Paris, or of lime and zinc oxides in sodium silicate. Tanks of different sizes are useful. The blocks of glass are held on a simple wire holder and immersed with it into the refractive liquid. The refractive liquid tank is kept covered as much as possible in order to prevent losses by evaporation and to hold the refractive index of the liquid constant. In place of carbonbisulphide which has many unfavorable properties, α-monobromnaphthaline[76] may be used. It is an oily liquid and leaves an oily film on

[76] Halowax oil, a cheap, impure form of monochlornaphthaline, was also tried.

each piece of glass examined. The carbonbisulphide volatilizes completely, leaves no film, and is ideal in this respect.

A simple method for adjusting the refractive index of the liquid mixture to that of an immersed glass fragment is to sight through any wedge-shaped (prismatic) edge of the piece of glass toward a narrow slit of light, such as a single filament of an electric bulb. Compare the position of the light filament when observed through glass and liquid and then through the liquid alone. In case, on interposing the glass fragment, the filament appears to move toward the thick end of the wedge-shaped glass piece, the index of the liquid is too low, and vice versa. If the liquid and glass prism have the same refractive index for the central part of the spectrum (yellow to green) there is no appreciable shift of the filament on insertion of the glass fragment in the path of light. If viewed under oblique illumination under the conditions of equal refractivity for yellow light the edges of the glass fragments show red and blue and purple colors.

This method of liquid inspection has many features in its favor and was operated successfully at the Pittsburgh Plate Glass Co.; but at the Bausch & Lomb plant, in spite of the most improved system of ventilation and special booths for the purpose, the workmen refused to use the method after a few days trial. In case a suitable high refracting liquid were available which is not poisonous and evil-smelling, the method would be adopted in all glass plants and much labor and expense thereby saved. The immersion method is useful for the rapid determination of the refractive indexes of glass samples and is valuable in separating plates or fragments of different glasses which may have been mixed through error.

From one-third to one-half of the pot glass is commonly discarded as cullet or is lost by the breaking and trimming operations preparatory to flattening.

THE MOLDING AND PRESSING OPERATIONS.

The trimmed, but still irregular, blocks are now flattened into place of different thicknesses either by molding or by pressing. In European practice has always been to mold the glass, but in this country the pressing method was largely used during the war. Experience with both methods indicates that for small blocks of glass the pressing method is preferable to the molding method, but that for large blocks or thick plates the latter is superior and that less glass is wasted by this method than by the pressing method.

The pressing process.—The prepared blocks are put into a preheating kiln and are slowly heated over night to 450° to 500° C., depending on the kind of glass. They are then placed as needed into the muffle, which is heated by a gas-air blast playing from a side entrance over the arch of the muffle. Heat radiates from the crown of the

muffle to the base plate on which the pieces of glass rest. Soon the glass begins to soften and the operator prevents it from sticking to the base plate by moving it along and by spreading over the slab a mixture of some refractory powder, such as clay and mica, or alumina, or diatomaceous earth or talc or fine graphite or a mixture of these; the fine powder sticks to the glass like flour to molasses taffy or to dough and shields it from the plate. The base plate itself is generally made of fire clay, but it may be of porcelain or of fused silica with a little less binding material, in which case practically no additional powder is required. Specially prepared plates of graphite, mica, and clay are also employed. The object desired is to prevent the molten glass from sticking and at the same time to avoid, so far as possible, a heavy coat of powder over the glass surface, which on pressing may be infolded and produce feathers, laps, and folds. For some purposes it is advantageous to heat the base-plate from beneath in order to avoid a one-sided heating of the glass pieces. Heating by radiation from the crown of the muffle liquefies the upper part of the glass block so that it flows down and spreads out beyond the cooler bottom resting on the base plate.

As the glass becomes softer the operator paddles it into shape with iron rods, flattened at the ends, and may thereby in certain pieces infold some of the dust-covered surfaces into the glass mass. The operator endeavors to shape the glass pieces so that they fit into the press mold properly. As soon as the glass has attained the proper shape and temperature (750° to 900° C.) it is transferred to a preheated iron mold and then placed under the heated plunger of a foot or pneumatic or hydraulic press and flattened to the desired thickness (fig. 53). The flattening operation takes less than a second; during this time the molten glass mass, which is of the consistency of thick tar, must flow under forced pressure; it does so somewhat after the manner of lava, in waves, the troughs of which are liable to be engulfed in the flowing mass and to appear then as "pressing defects," "feathers," "folds," "laps" in the finished glass plate. With careless manipulation a very large percentage of all glass can be rendered useless during this operation. In place of a mechanical press, the workman may shape the glass block to proper size by use of the iron paddles alone. This is, of course, a slow operation, but there is less danger from defects with this method. The rapid action of the plunger of the press is necessary because the outer surface of the glass block chills rapidly in the open air and becomes so stiff that soon the block can no longer be pressed into shape.

If the iron mold or plunger is not hot enough, the surface of the pressed plate is chilled too rapidly and becomes filled with fine transverse cracks; in the case of a cold mold the crackling may be so pronounced that it resembles the "craze" of ornamental glassware.

In the pressing process an iron or steel mold of the desired depth is is used. The plunger reaches the rims of the mold and presses the glass to this thickness; in order to accommodate the mold to blocks of different sizes it is closed on the sides and at one end only. A plunger from the other end fits nicely into the mold and slides into it just after the vertical plunger acts and presses the glass into square ends. This operation enables the operator to obtain plates of con-

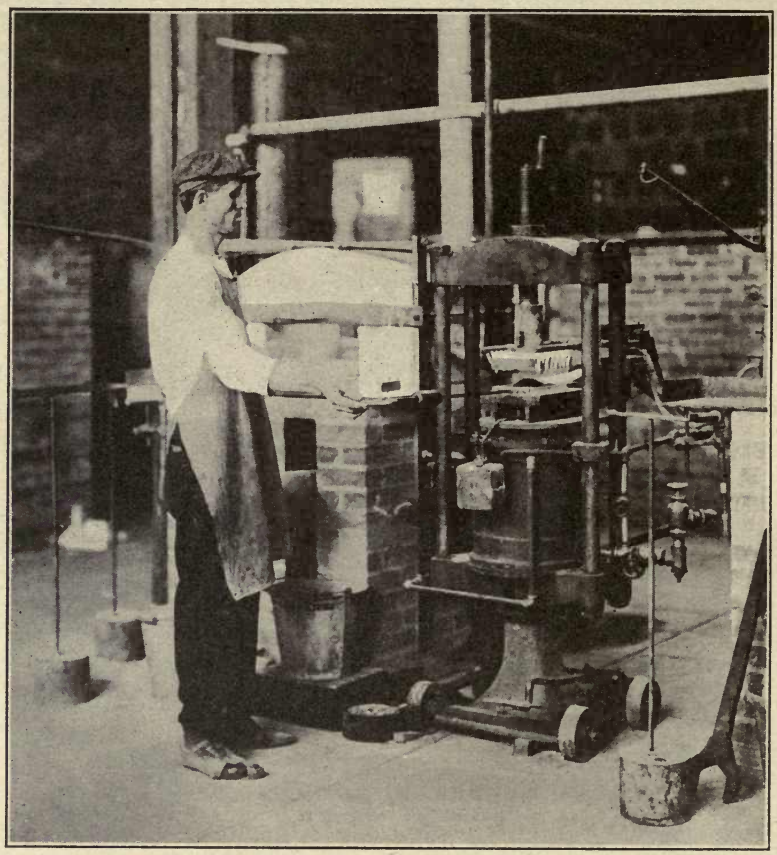


FIG. 53.—Block of glass in mold and ready to be pressed into plate by plunger of hydraulic press. (Photograph by J. Harper Snapp at plant of Bausch & Lomb Optical Co.)

stant thickness and width but of variable length; the side plunger introduces, however, further infolding of the molten glass and may occasion serious loss if not handled properly. In many cases it is better not to use the side plunger, even though the ends of the plate do not then come out square. The advantage of the pressing process is that plates of uniform thickness and width are obtained; its chief defect is the loss of glass occasioned by pressing defects. An advantage of the pressing process is that the number of the pot, the refrac-

tive index and ν-value, and other desired information may be imprinted on the block during the pressing operation.

A plan to avoid the danger from pressing defects and yet to retain the advantages of the pressing method was proposed by Capt. H. C. Fry, jr.,[77] and put to practical test on a small scale at the optical-glass plant of the Bureau of Standards in Pittsburgh. His method is essentially an adaptation of the method, used in ordinary glass factories, of gathering the desired amount of molten glass on the end of an iron rod (punty) and transferring it then to the press. In the case of optical glass a block of glass is first slowly heated up to near the softening point and is then stuck at one end to a bleb of molten glass of the same kind at the end of a punty; on the punty it is heated and reheated carefully in the direct flames of a glory hole and is paddled with proper shaping tools from time to time to approximately the desired shape. The actual pressing operation does not then involve much deformation of the glass mass and the danger of infolding is thus reduced to a minimum. Plates, prisms, and lenses pressed by this method have clean surfaces like the glassware produced in ordinary glass factories and are free from feathers. Compared with the ordinary method, this method is much slower and only an actual factory test can demonstrate whether its advantages of better quality of product outweigh the disadvantage of greatly decreased rate of output.

The molding process.—In this method the irregular pieces of glass are taken as they come from the trimmer (practically in the shape as they are broken from the pot because trimming is less essential in the molding process than in the pressing process) and are placed in molds of proper sizes, which are then set at the cool end of a tunnel about 20 feet long, 2 feet wide, and 10 or 12 inches high, inside dimensions; the molds are pushed gradually, one behind the other, toward the hot muffle end of the furnace; about 6 feet from the hot end of the tunnel a clay partition or curtain extends to within 4 or 5 inches of the floor and serves to confine the heat to a certain extent. The molds on reaching this part of the furnace have attained a temperature of 500° or 600° C. and may then be thrust into the hot muffle chamber where the temperature rises rapidly to 1,100° and even to 1,200° C. This abrupt rise in temperature is valuable for several reasons; the heat in the muffle is derived from the heated arch by radiation; the glass is therefore heated largely from the top down. By melting down the glass from the top the liability to formation of bubbles is largely avoided; furthermore the glass is taken rapidly through the critical temperature range of devitrification with respect to any one of the components; within this range, precipitation may

[77] J. Am. Ceram. Soc., 2, 432, 1003, 1919.

occur either as crystallization and the formation of a devitrified crust, which is very difficult to remove, or as a milky, colloidal development which is even more serious. In fact, by this process opalescent glass becomes in some instances clear and satisfactory for optical purposes. Once the molds enter the heated chamber the glass melts down rapidly. The molds are gradually pushed forward from the cool end; the hot molds are removed from the muffle end.

The time required for the entire process is about two and one-half hours; approximately 25 molds are kept in line; the output per tunnel per day of 24 hours is from 400 to 500 molds. The molds are transferred to a cooling arch, where they are stacked and allowed to cool down slowly for several days. It would be a great improvement if the molding tunnel were heated electrically and made much longer so that the annealing of the molded plates could be accomplished in the same tunnel, thus avoiding the necessity of transfer to an annealing kiln or lehr. In this case careful regulation of the temperatures would be required and also probably an automatic feed to carry the moulds through the tunnel at the prescribed rate.

The tunnels are simple in construction and can be built side by side, each offset, echelon fashion, to give room for the muffles. The wear on clay molds is severe; the life of a mold averages about three runs through the tunnel; cast-iron and other metal molds have been used with some success. The temperatures required in the muffle furnace vary with the type of glass; the workman learns readily from the behavior of the glass in the molds to regulate the gas blast so that the optimum conditions for each type of glass are obtained.

The molding tunnels may well be designed so as to have a curtain chamber beyond the muffle in which the molds can cool down to, say, 600° C, or lower in the case of flint glasses; the glass plates may then be dropped from the molds and transferred to the annealing kiln. At these temperatures neither the glass nor the molds are so brittle as at ordinary temperatures, and they can be handled roughly without danger of breaking. The advantages of this procedure are obvious; the glass plates in sliding into the cooling chamber are not tilted, and consequently cool down on even keel; the removal of the mold from the glass greatly increases the capacity of the annealing furnace. The danger of cracking in the molded glass plate, because of the different rate of contraction of the clay mold, is also eliminated by this operation. In the barium crown glasses cracking of plates cooled down in the molds may be serious. In all work of this kind the annealing furnace should not be heated so hot that the inserted plates bend out of shape.

Before introduction into the tunnel the molds with glass blocks may be preheated by placing them above the molding tunnels, thus expediting the actual tunnel treatment. The chief difficulties and

losses in the molding process arise from the glass plates sticking to the molds; in removing the glass plate either it is broken or the mold is broken, or both. To prevent the glass plates from sticking, the mold is lined with a slip consisting of mixtures of clay and mica or sand, or of alumina, talcum powder, graphite, or other refractory material. If the slip is too thick, some of the powder may be carried up into the molten glass. In the molding operations the best conditions of treatment for each type of glass are ascertained only by experience with each kind of mold in each type of tunnel. Porcelain molds have been found to be more satisfactory than the ordinary clay molds, which have a tendency to produce bubbles in the molded plates.

Examinations of many hundreds of plates of molded glass, both foreign and domestic, proves that the molding process produces plates freer from defects than are pressed plates. It is therefore less wasteful of glass than the pressing process and is nearly as efficient and rapid, especially for larger plates; for small lens and prism blanks, the pressing method is obviously superior.

The molding process is most valuable for the molding of large blocks from which large prisms can be sawed directly. The quality of the glass blocks can be approximately determined as they are taken from the pot; the molding process tends to confine existing defects; the pressing process tends, on the other hand, because of the rapid flow of glass, to cause existing striæ to spread out into the good glass and also to introduce infolded portions of the clay and dust between surfaces of the paddled piece of glass.

One disadvantage of the molding process is the fact that by it the plates can not be automatically labeled with pot number etc. as they can by the pressing process.

In both pressing and molding processes the workmen must be trained to the tasks and carefully supervised, otherwise much good glass may be wasted as well as time and expense.

THE ANNEALING OF MOLDED OR PRESSED PLATES.

The general principles, on which methods for annealing optical glass are based, have already been stated in the section on the cooling down of pots of optical glass. These principles were known in part when we entered the war, but the details, especially the temperature to which each type of glass should be heated for annealing and also the time-temperature relations during the cooling of the several types of glass, had to be ascertained by actual experiment. Accordingly a simple arrangement was adopted which enabled us to observe the course of annealing at all stages of the process. (Fig. 54.) Most of the experimental work was done in a small, gas-heated kiln through the back of which a hole was drilled to allow a beam of plane-polarized light to traverse the furnace. A beam of

plane-polarized light was obtained by reflection of rays from an intense light source by a plane polished plate of opaque glass mounted at the proper polarizing angle; this beam of polarized light traversed the glass plates in the furnace in a horizontal direction and was analyzed by means of a nicol prism and a sensitive tint plate held outside and in front of the furnace, the end openings in the furnace being protected by thin glass windows. By means of this simple arrangement the exact state of strain in a plate in the furnace could be ascertained at any time and its temperature measured by means of a thermoelement and a millivoltmeter or a potentiometer system. Series of strain-temperature-time measurements on plates of the several different types of glass were made and from these practical annealing schedules were worked out which proved satisfactory in practice. In point of actual time expended and of difficulties encountered the

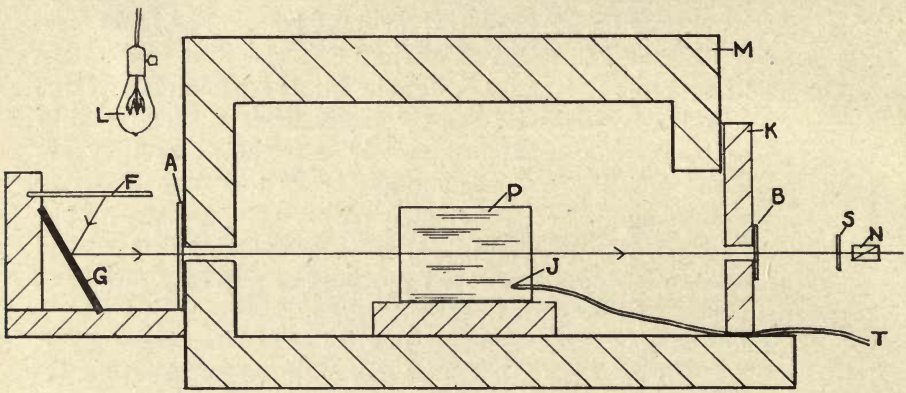


FIG. 54.—Simple arrangement adopted for the study of strain-temperature-time relations in optical glass. *L* is an electric bulb; *F*, a plate of frosted glass; *G*, a piece of opaque glass placed at the polarization reflecting angle; *A*, a piece of thin glass; *M*, the gas-heated annealing oven; *P*, the glass plate under test; *T*, the thermoelement; *B*, a thin glass window; *S*, a sensitive-tint plate: *N*, the analyzer.

general factory problem of annealing proved to be one of the easiest to solve and to put into routine practice. From a theoretical viewpoint it is, however, an exceedingly complex problem and many of the factors involved are inadequately known even at the present time. A brief summary of the problem will serve to indicate some of the difficulties which it presents.

At high temperatures glass is a mobile liquid; at room-temperature it is practically an elastic solid. On cooling from a high temperature the fluidity of molten glass decreases with fall in temperature until its tendency to flow, in the ordinary sense of the word, ceases; the liquid gradually congeals, as it were, and passes from a viscous, fluent body to a plastico-viscous body; with still further decrease of temperature the elastic qualities begin to dominate until at room-temperature but little evidence of plasticity or viscosity remains. This passage from the one condition to the other is a continuous

process except for a small temperature interval just below the softening region at which the glass begins to flow; in this temperature region [78] there is a rapid rise in the expansion coefficient accompanied by a distinct heat effect (evolution of heat on cooling and heat absorption on heating). The temperature region of special importance in glass annealing has for its upper limit that temperature at which glass is just able to support deformational loads, and hence internal stresses, for appreciable periods of time; from this temperature down to room-temperature the behaviour of glass is interesting to follow.

Twyman and others have shown that for the first 100° or 200° C. below the softening temperature (the annealing range) the viscosity is doubled with each drop of about 8° C. in temperature, or $M = K.2^{\frac{\theta}{8}}$ in which M is the measure of the rate of deformation at a given temperature, K is a constant depending on the kind of glass, and θ the temperature. If glass were a perfectly elastic body, Hooke's law, that the stress is proportional to the strain, would apply, or $S = E \cdot B$ in which S is the stress, B the strain, and E the modulus of elasticity. The change of stress with time C would be accordingly proportional to the change of strain with time or $dS/dt = E \cdot dB/dt$. At the higher temperatures glass is not perfectly elastic and internal stresses, set up by initial strains, are gradually relieved by flow. The simplest assumption, made first by Maxwell [79] is that the rate of relief at a given temperature varies with the stress and the kind of glass or $dS/dt = E \cdot dB/dt - S/T$ in which T is a constant, the "time of relaxation" as designated by Maxwell. If the strain B is constant, as it is in the case of a body under deformational load at constant temperature, or if it changes only slightly with time, we may write as a first approximation

$$dS/dt = -\frac{S}{T}, \quad \text{or } S_t = S_o e^{-\frac{t}{T}}$$

an equation which represents the course followed in the release of the inner stress; S_o is the initial stress; S_t the stress after the time t. If on the other hand the stress, S, is constant, as it is in the case of a glass rod under compression or tension, then $S = E \cdot T \cdot dB/dt$. By measuring the rate at which the glass rod is deformed with time for a given load S we can compute the time of relaxation T; this is the time, according to Twyman, required for annealing the block of glass stressed to the given amount and held at the given temperature. Twyman states that his experimental results corroborate the above assumption suggested tentatively by Maxwell. Adams and William-

[78] Tool and Valasek, Bureau of Standards, Paper No. 358, 1919; Peters and Cragoe, Jour. Opt. Soc America, IV, 105-144, 1920.

[79] Phil. Mag. (4), 34, 129, 1868.

son, on the other hand, state that their more recent data indicate that the relief of stress by flow at a given temperature is proportional not to the stress but to the square of the stress or

$$dS/dT = E \cdot dB/dt - S^2/T$$

from which we derive for a constant load ($dS/dt = O$),

$$S^2 = T \cdot E \cdot dB/dt;$$

and for constant strain ($dB/dt = O$),

$$dS/dt = \frac{S^2}{T}, \text{ or } \frac{1}{S} - \frac{1}{S_o} = \frac{t}{T}.$$

In 1912 Zschimmer and Schulz [80] carried out a series of experiments on the amount of strain introduced on the rapid cooling of blocks of glass from different temperatures and found that the effect of temperature within the annealing range on the total amount of strain produced is represented by the empirical equation

$$(S_o - S) \cdot (\theta - \theta_o) = C$$

in which S_o, θ_o, and C are constants, S, the strain, and θ the temperature from which the glass was chilled. These results of Zschimmer and Schulz are not, however, directly applicable to the above problem and will not be considered further.

The coefficient of expansion is practically linear up to a temperature not far below the softening temperature. (Table 10, p. 153.) The temperature distribution in solids of different shapes and sizes during heating or cooling has been investigated repeatedly, especially from a mathematical standpoint; and recently Williamson and Adams have considered the subject with special reference to glass bodies heated either linearly or with the surfaces held at a definite temperature. In the study of strained glass samples optical methods are especially useful and are based on the relation first discovered by Brewster that in a glass block under load the optical effect produced (birefringence or optical path difference per centimeter glass-path) varies directly as the load; in other words, the stress is proportional to the birefringence and the observed changes in birefringence may serve as measures of the relative changes in the stresses. The relations between birefringence and stress in various types of glass are listed in Table 11, as determined by Pockels and Adams and Williamson. Mathematical analysis of the strains and stresses in solids due to temperature gradients was first given by F. Hopkinson and recently has been presented by Williamson with special reference to optical glass solids of simple shape.

With these relations in mind let us follow the changes in a block of glass roughly spherical in shape and initially heated to a uniform

[80] Zeits. f. Instrumentenkunde, 33, 303, 1912; Sprechsaal, 47, 460–478, 1914; Ann. d. Phys. (4), 42, 345–396, 1913.

temperature slightly below its softening temperature as it cools down to room temperature. The glass adjacent to the surface cools at first more quickly than the interior, and in so doing contracts and tends to squeeze the center thereby setting up stresses of radial compression throughout the mass. As the temperature gradient increases on further cooling of the glass mass the amount of stress introduced increases throughout the mass.

If given sufficient time, the temperature gradients or the differences in temperature between the center and different points along a radius approach a steady state as indicated in (fig. 55) and if the cooling were to continue as linear cooling this temperature gradient would persist. The strains, thus set up on cooling, produce stresses in the glass mass which at the higher temperatures are in large measure relieved by actual internal flow. If the cooling were to proceed with sufficient slowness, the entire stress at any high temperature could be relieved. If the normal temperature gradient were established at a sufficiently high temperature, all stresses would be relieved by flow, and if this temperature gradient were maintained until the surface of the mass reached room temperature no stress would be present at that instant. From here on however, strain would be introduced rapidly, because of the cooling of the center and its consequent contraction and tendency to pull away from the outer shell, thus setting up stresse of radial tension, and accompanying tangential compressive stresses near the periphery; toward the center these tangential stresses decrease, become zero, and pass into tangential tensional stresses which at the center are equal to the radial stresses.

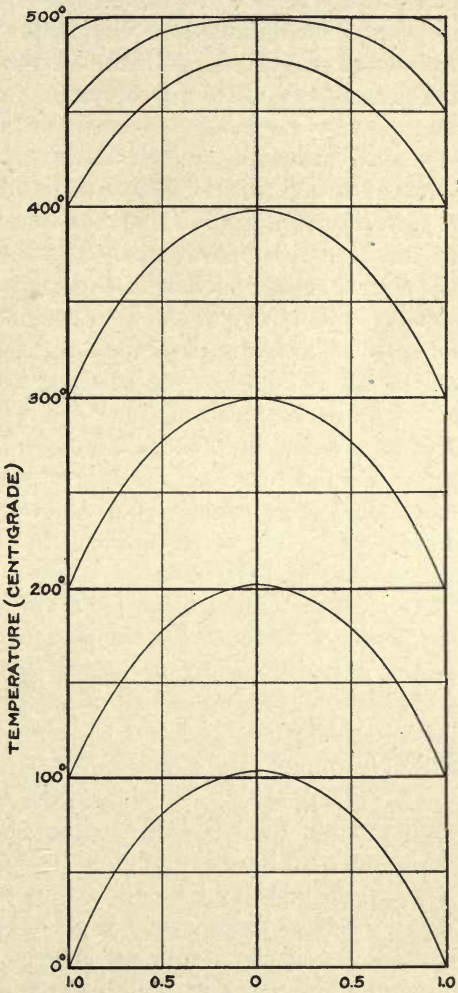


FIG. 55.—Curves representing the temperature distribution in a sphere of glass of unit radius cooling at a linear rate from 500° C. to 0° C. The zero abscissa represents the center of the sphere.

In general the rate of cooling is not linear nor is all the stress relieved by flow. Obviously less stress is introduced and more existing stress is relieved by flow the more slowly the glass mass is cooled. The result is that the temperature gradient becomes a maximum and then decreases with further cooling until it disappears at room temperatures. While the temperature gradient during this process is increasing the outside is cooling faster than the center and introducing stresses of radial compression. These are in part relieved by flow, so that the optical effect observed is not so great as it would be for a temperature interval of equal amount in a glass mass in which the stress had been maintained at its full value. On further cooling the temperature gradient is reversed and the center begins to cool more rapidly than the periphery, thus neutralizing the stresses introduced at the higher temperatures. There is this difference, however, that the rate of relief of strain at the low temperatures is exceedingly slow, so that little if any of the stresses introduced are relieved by internal flow. The result is that not only are the stresses which were introduced at the high temperatures neutralized, but radial tensional stresses are set up in amount equal to the algebraic sum of the two sets of stresses involved. The normal state of stress in a body at room temperature is accordingly that which results when the center has cooled more rapidly than the outside. This view of the subject was apparently first emphasized by Twyman, and more recently by Williamson and Adams.

As a further illustration let a block of glass be heated from room temperature to 100° C., a temperature at which stress is not relieved appreciably in a short period of time. Let the glass block be free from strain at room temperature. On heating the glass, strain is introduced into it and can be readily measured by the polariscope. This strain reaches a maximum and then begins to decrease and finally disappears completely with the attainment of the uniform temperature, 100 °C. On cooling, the reverse phenomena can be observed. So long as the glass behaves as a strictly elastic body the above relations hold true; but, if at any temperature part of the stress is relieved by viscous or plastic flow, the phenomena cease to be reversible and the statement is then to that extent incorrect.

Having determined the temperatures for the several types of glass at which strain is relieved within a reasonable time and having ascertained the times required at several different temperatures to reduce the stress to a certain limit the observer still requires data on: (*a*) The limits of permissible strain in optical glass when used for different purposes; (*b*) the time-temperature rate of cooling in order that strains of appreciable magnitude are not introduced during the cooling period. For the specification of permissible strain a large number of plates of optical glass of different types, made by Chance Bros., in

England, by Parra-Mantois in France, and by Schott and Genossen, in Germany, were examined in polarized light and the amount of maximum birefringence or the path difference per centimeter glass-path was measured in each piece. This examination showed that the maximum path difference for sodium light per centimeter glass-path rarely exceeded 30 millimicrons and was commonly not over 10 millimicrons. These values were characteristic of glass which before the war had been used for optical instruments of the most diverse kinds, such as range finders, telescopes, field glasses, microscopes, surveying instruments, and had proved satisfactory in actual use. The maximum limit for permissible strain was accordingly arbitrarily set as that which produced a maximum path difference of 20 millimicrons in a plate when viewed through the edges. This corresponds to a path difference of 10 millimicrons per centimeter glass-path at the center of the plate or a birefringence, 0.000001. The methods for detecting and measuring these quantities are described in the next chapter. It was also stipulated that the strain distribution should be sensibly symmetrical in the plate and that local irregularities should not be present.

For a determination of the time-temperature cooling rate the law of Twyman was available that the mobility of glass decreases logarithmatically with the temperature; also the statement by Twyman that his measurements corroborated the assumption made by Maxwell, as a first approximation, that the time of relief of stress at a given temperature is proportional to the stress itself.

By means of the arrangement described above for the study of strain in optical glasses (fig. 54) the temperatures at which the strain disappears very rapidly was found to be (heating rate 40° to 75° C. per hour) in borosilicate crown 590° C., in light barium crown 600° C., in ordinary crown 540° C., in light flint 500° C. At 550° C. the strain disappears from a plate of borosilicate crown in a few hours; at 510° C. over night; at 480 ° C., 24 hours are not sufficient for the removal of the strain. These and other measurements together with Twyman's work enabled us to set up annealing schedules which produced glass plates as well annealed as the best foreign glass. The annealing schedules were so arranged that, after insertion of the plates into the annealing kiln, it was held over night at a temperature such that by morning the entire glass charge would be at a uniform temperature and practically free from strain. This temperature was of course different for different glasses and was commonly 25° to 50° C. below the foregoing temperatures, at which the strain disappeared very rapidly. The furnace was then cooled down at an increasing rate in order to avoid the development of strain. The ideal type of time-temperature cooling curve for the annealing of glass is convex upward; the natural curve of a furnace is concave

upward. The time-temperature curve of a cooling kiln may be made to approximate the proper annealing curve by proper regulation of the heat. More accurate and detailed data on the relaxation times (time required to reduce strain-birefringence of different types of glasses from $50 \cdot 10^{-7}$ to $5 \cdot 10^{-7}$ are given in Table 10 quoted on page 153 from Adams and Williamson whose measurements are more recent and were made under accurately controlled laboratory conditions.

Essential for the proper annealing of optical glass is the annealing furnace. Furnaces of the proper design may be heated either by gas or by electricity. The object to be attained in all designs is uniformity in temperature distribution throughout the entire space occupied by the glass. In the case of a gas-heated furnace this is attained by the use of long perforated gas pipes which serve as gas burners for the gas-air mixture and which extend the length of the furnace and are situated below the two breast walls. Commonly no flue or stack is used to conduct away the products of combustion. In case such flues are used they should be located at intervals in the arch of the kiln and be equipped with dampers so that the flow can be nicely regulated. Any design which sets up a draft in the furnace may introduce currents within the heating chamber and thus give rise to inequalities in temperature distribution.

A reliable and accurate thermoelement installation for the measurement of furnace temperatures is a second necessity. This consists of two parts; the thermoelement (base metal thermoelements answer the purpose well) in which an electromotive force is set up between the hot and cold junctions, the magnitude of this force depending on the temperature difference between the two ends; an instrument for the measurement of the electromotive forces thus set up; this may be either a potentiometer or a direct reader. Experience proved that the potentiometer type of instrument is preferable to the direct reader (millivoltmeter). Because the temperature difference depends directly on the temperature of the cold junction as well as on that of the hot junction, it is essential that the temperature of the cold junction be kept as nearly constant as possible. A practical method to insure this constancy is to bury the cold junction 8 or 10 feet under ground and at some distance from the annealing furnace.

It is also essential that the thermoelements be tested frequently (at least once a month and as a routine job) and the correctness of their readings ascertained. For this purpose additional thermoelements should be kept on hand so that they may be substituted for thermoelements under test, thus insuring continued operation of the annealing furnaces. A convenient standard temperature for reference is that of melting tin which can be kept in a pure state without trouble. It is best to introduce the thermoelement from the top of

the arch of the furnace and to allow it to extend well into the heating chamber.

A record should be kept of the quality of the annealing of each lot of glass. The glass may for the purpose be divided into the following classes:

Class 1. Annealing excellent. Maximum strain-birefringence less than $5 \cdot 10^{-7}$ or 5 millimicrons per centimeter glass path.

Class 2. Annealing good. Maximum strain-birefringence between $5 \cdot 10^{-7}$ to $12 \cdot 10^{-7}$.

Class 3. Annealing fair. Maximum strain-birefringence between $12 \cdot 10^{-7}$ and $20 \cdot 10^{-7}$ and symmetrically distributed.

Class 4. Annealing poor. Strain-birefringence greater than $20 \cdot 10^{-7}$ or, if less, then not symmetrically distributed.

The following records of annealing at the Bausch & Lomb plant, supervised by G. W. Morey on January 15, 1918, in routine factory kilns, each with a capacity of more than a ton of glass in pressed plates arranged in the furnace so as to allow some circulation of air, may be of interest. The furnace schedule in the case of the borosilicate was the following: Temperature during filling-in period from 1.40 p. m. to 4.10 p. m. 565° C. (1,050° F.). Temperature maintained at 565° C. (1,050° F.) until midnight, then slowly dropped to 524° C. (975° F.) at 8.30 a. m., to 432° C. (810° F.) at 1.30 p. m. Gas was then turned off and furnace allowed to cool down. Glass removed the following day. Of the 694 plates examined in this lot 82.5 per cent were in class 1, 9.5 per cent in class 2, 7.7 per cent in class 3, and 0.3 per cent in class 4. In another lot of 1,019 plates annealed at different times and of different kinds of glass, ranging from 9 millimeters to 30 millimeters thickness, 93.5 per cent were in class 1; 4.4 per cent in class 2; 1.3 per cent in class 3, and 0.8 per cent in class 4. It is difficult to avoid a certain number of poorly annealed plates; these may have rested next to the bottom of the kiln or been near the front and chilled by air currents.

Annealing schedules for various kinds of glass.—In a recent publication on the annealing of glass, Adams and Williamson[81] present in tabular form annealing schedules for glass slabs of different types and thicknesses. These schedules are based on extended mathematical and experimental investigations and are the best available schedules at the present time. With slight modifications they can be adjusted for other shaped pieces of glass, such as prisms, lenses, spheres, cylinders, etc. These schedules are listed in Table 14 reproduced from the paper by Adams and Williamson.

[81] Jour. Franklin Inst., 190, 850–856, 1920.

TABLE 14.—*Annealing schedule for optical glass slabs of different thicknesses; the strain of the annealed plate, as measured optically in polarized light when the slab is viewed through the edges, not to exceed an optical path difference of 5 millimicrons per centimeter glass-path.*

[Hold the glass at the proper annealing temperature for the indicated time and cool at the indicated rate.]

Kind of glass.	Thickness. Annealing temperatures, degrees centigrade.				
	1 cm.	2 cm.	5 cm.	10 cm.	20 cm.
Borosilicate crown	561	541	515	495	475
Ordinary crown	535	514	487	466	445
Light barium crown	571	552	527	508	489
Dense barium crown	608	592	572	556	540
Barium flint	516	494	466	454	423
Light flint	427	408	384	366	348
Medium flint	434	418	397	382	366
Dense flint	424	407	386	370	353
Extra dense flint	400	382	357	339	321

Annealing times.—Cooling rates, degrees centigrade per hour.

	50 minutes.	3½ hours.	21 hours.	86 hours.	14 days.
Initial rate	96	24	3.8	1.0	0.2
Rate after 10°	116	29	4.6	1.2	.3
Rate after 20°	144	36	5.8	1.4	.4
Rate after 30°	184	46	7.4	1.8	.6
Rate after 40°	240	60	9.6	2.4	.6
Rate after 50°	319	80	13.0	3.2	.8
Rate after 60°	432	108	17.0	4.3	1.1
Rate after 70°	591	148	24.0	5.9	1.5
Rate after 80°	816	204	33.0	8.2	2.0
Rate after 90°	1,134	283	55.0	11.0	2.8
Rate after 100°	1,584	396	63.0	16.0	4.0
Maximum cooling rate	2,400	600	96.0	24.0	6.0
Maximum heating rate	7,200	1,800	288.0	72.0	18.0

Although the factory annealing of plates of pressed lens blanks and of prisms is not difficult, yet it requires constant supervision with reference both to the maintenance of the furnace temperatures and to the furnace schedules for the type and sizes of blocks of glass under treatment. The thicker the plate of glass the slower must be the initial rate of cooling from the annealing temperature. The permissible initial rate of cooling decreases about as the square of the reciprocal of the thickness; for example, a satisfactory initial cooling rate for a plate of borosilicate crown 1 centimeter thick is 20° F. (11° C.) per hour; for a plate 2 centimeters thick, the proper initial rate would be about 5° F. (3° C.) per hour.

In the case of a lehr the rate of annealing is of course much more rapid; thus most of the flint glass in plates 9 millimeters thick and also small lenses and field glass prisms were satisfactorily annealed during the war in a lehr in a period of 9 to 18 hours. Here again the temperature distribution and the rate of travel of the glass through the lehr requires proper supervision and regulation to avoid abrupt changes in temperature as well as air currents which may chill the plates.

THE GRINDING AND POLISHING OF PRESSED OR MOLDED PLATES OF GLASS PREPARATORY TO INSPECTION.

After removal from the annealing furnaces the plates are inspected, in the rough, through the ends for quality of annealing and are then sent to the grinding and polishing tables where they are made ready for critical inspection for striae, bubbles, stones, and pressing defects. For this purpose the plates are ground either on the sides or on the ends or on both. European optical glass is shipped in plates ground on two opposite ends for inspection. A molded or pressed plate of glass examined critically under these conditions and found to be free from striæ is probably free from any striæ which would cause trouble in an ordinary optical lens system. If, however, striae are observed, either the plate should be discarded as a whole or the striated portions should be trimmed off; but in performing this operation much good glass may be lost because the exact positions of the striae in the plate are not easy to determine under the conditions of observation. The plate may be rotated about different axes and the position of a stria approximately located and then trimmed off; but after this has been done reinspection of the plate is possible only with the aid of an immersion liquid.

The grinding and polishing of the plates on the sides (flats), on the other hand, enables the inspector to mark the striated or otherwise unsuitable portions plainly during the inspection; these can then be readily trimmed off and discarded so that the remainder of the plate is of first quality glass; such a plate can moreover always be reinspected directly, because the trimming away of a striated portion does not destroy the remainder of the plane surfaces. It is true, on the general law of probability, that inspection through the ends of a glass plate enables the observer to detect fine striae more readily than through the flats chiefly because of the much longer glass path examined by the first method; but the available methods of inspection are sufficiently sensitive in general to inhibit the release of much striated glass by a good inspector. To be thoroughly satisfactory the glass plates should be inspected both through the ends and also the flats. This is evident when plates of rolled or plate glass are inspected for striae; such plates, examined through the flats, appear to be free from striae, but when viewed through the ends, they are seen to be filled with bands of striae or ream running parallel with the flat surfaces of the rolled sheet.

The polishing of pressed or molded plates on the ends represents a great saving of time and expense and also of the glass itself as compared with polishing on the flats. In general it may be stated that for glass relatively free from striæ polishing on the ends is to be recommended. If, however, striæ are abundant and it is desired

to eliminate these by trimming, the plates should be ground and polished on the flats. In case glass of the highest quality is desired the plates should be polished both on the flats and on at least two opposite ends.

The grinding and polishing of the plates is not a matter of much difficulty. Ordinary factory methods for grinding and polishing are employed (figs. 56 and 57), an effort being made to arrange the machines and the operations in such order that a large quantity of glass can be handled expeditiously and cheaply. Polishing on felt is sufficiently good for the purpose and is much more rapid than polishing on pitch. In the case of pressed plates to be polished on the ends, the blocking of the plates may be done by the use of clamps

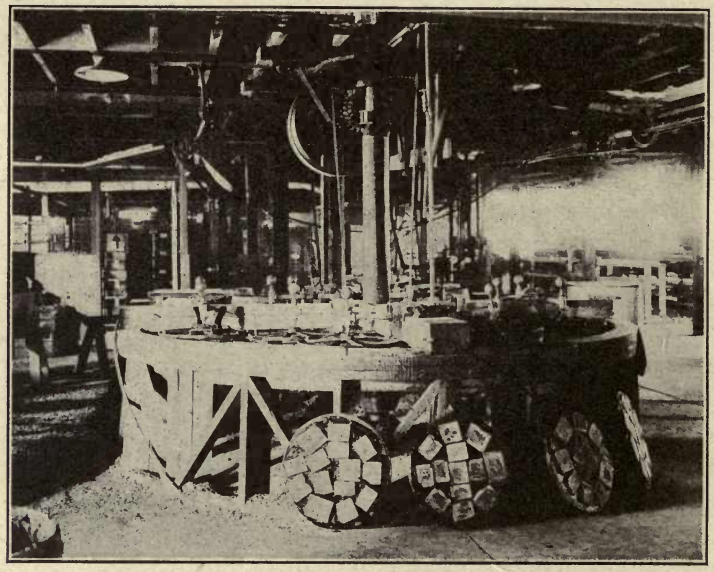


FIG. 56.—Rough grinding wheel for grinding plates of optical glass. (Photograph by J. Harper Snapp at plant of Spencer Lens Co.)

which hold the plates in position between pieces of felt and without the aid of pitch or plaster of paris; much time and expense are saved thereby.

War-time experience showed that, in the case of rolled glass, inspection was possible for ordinary requirements through the fairly smooth fracture surfaces obtained by cutting the sheet of glass into squares by means of a glazier's diamond or a glass cutter's wheel. In this case the striæ or ream are all arranged in parallel sheets and are readily detected.

The plates after polishing are thoroughly washed and cleaned in hot alkali and soap solutions and are then ready for critical inspection. In case no defects are then found in a given plate it is a finished

product, so far as the optical glass plant is concerned, and is ready for shipment to the maker of lenses and prisms for optical instruments.

In case the inspection reveals the presence of defects, such as striæ, bubbles, stones, pressing feathers or folds, or other defects in a plate, it is rejected and returned to the trimmers for elimination of the sources of trouble. Striated portions are trimmed off, pressing defects are trimmed and ground off, either by the use of special grinding tools or by a sand-blast. The fragments of good glass still remaining, if sufficiently large, are repressed, reground, and re-inspected; if only in small fragments they are either discarded or reserved for use in second-grade optical lens systems, especially cheap photographic lenses.

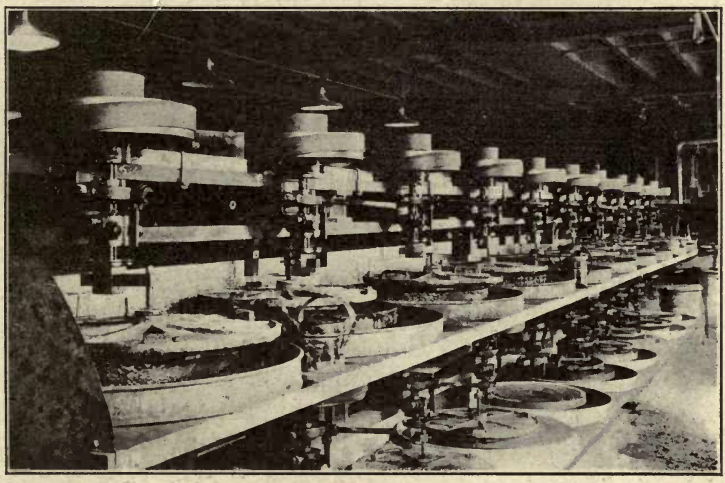


FIG. 57.—Grinding (lower row) and polishing (upper row) disks for plates of optical glass. (Photograph by J. Harper Snapp at the Hamburg plant of Spencer Lens Co.)

PERCENTAGE LOSSES OF GLASS IN THE FACTORY OPERATIONS.

The yield of good optical glass is not the same for each pot of glass, but varies within wide limits for different types of glass and for different pots of the same type. A yield of 10 to 20 per cent of good glass from a pot is generally considered to be satisfactory; but during the war period after the factory operations had been properly systematized the percentage yield of good glass in pressed plates was increased to 30 and 35 per cent and, in the case of a particular glass, rose to 50 per cent during one month at one of the factories. At first thought it may appear that these losses are excessive and with proper care might easily be reduced. This is no doubt true, but many of the losses are the result of mechanical operations and these can not readily be avoided. They do not necessarily indicate that the glassmaker is at fault. Even if the pot of raw glass were prac-

tically perfect appreciable percentage losses would result from the breaking up of the pot and from the several trimming operations, especially in preparing the glass for molding or pressing into plates. Many of the fragments obtained on breaking down a pot of glass are small and of irregular shape and therefore useless.

Although in actual factory routine the percentage losses caused by any given operation differ from pot to pot and from one type of glass to another, the following general percentage losses may be expected:

(*a*) Preparing raw pot glass for pressing or molding into plates, from 30 to 60 per cent.

(*b*) Molding or pressing operations, from 3 to 5 per cent.

(*c*) Grinding and polishing of pressed plates on flat sides, from 5 to 10 per cent. Grinding and polishing on ends of molded plates, from 1 to 5 per cent.

(*d*) Trimming of plates polished on the flats, from 10 to 15 per cent.

In the further preparation of inspected plates as material for lens and prism blanks which are trimmed to pieces of exact weight, there is a loss of 20 to 25 per cent of the weight of the plates or of 8 to 10 per cent of the original weight. In the lens and prism pressing operations a loss of about 10 per cent in the weight of glass plates or of 3 to 5 per cent of the weight of the original raw glass may occur.

At one of the factories a yield of 20.5 per cent of glass in the shape of lens and prism blanks was obtained over a considerable period of time. The yield in the form of inspected pressed and polished plates varied with the different types of glasses, but ranged between 20 and 50 per cent.

SUMMARY.

In this chapter the effort has been made to describe in a general way the processes involved in the manufacture of optical glass. The outstanding feature of these processes is not their intricacy or dependency on special apparatus of unusual or extreme characteristics, but their relative simplicity and dependency on accurate control, especially along chemical and thermal lines. Raw batch materials of high chemical purity, optical pots of high thermal and chemical resistance, accurate thermal regulation of the melting and annealing furnaces, and careful attention to schedules as part of the ordinary daily routine are necessary and essential to success in the manufacture of optical glass which has to meet the exacting requirements of high precision in so many respects. There is nothing secret or mysterious in its manufacture; but the organization which fails to appreciate the significance of high precision and of adequate scientific control and regulation can not expect to produce optical glass of uni-

formly high quality. This statement is emphasized because one of the greatest sources of trouble in the development of the war-time manufacture of optical glass on a large scale was the lack of appreciation on the part of certain manufacturers of this fundamental fact, and hence their lack of effective cooperation; this, together with a lack of trained personnel, both in the factories and in the inspection and other branches of the Army and Navy, added much to the difficulties of the situation during 1917 and the first half of 1918. During this time, moreover, no information or assistance of any kind was forthcoming from Europe. Fortunately, however, the difficulties were overcome, slowly at first and then more rapidly, so that by the end of 1917 no serious apprehension existed in the minds of the men actually engaged on the tasks regarding the final outcome, nor of our ability to meet all the demands of the military forces in the field.

Chapter IV.

THE INSPECTION OF OPTICAL GLASS.

Inspection has only one purpose wherever employed, namely, to eliminate the bad from the good and to grade the objects inspected into classes of different degrees of merit. In the manufacture of optical glass proper inspection is essential, and may not be neglected. In the absence of inspection, material of poor quality may continue on through many expensive and painstaking operations, all of which are then wasted, because eventual rejection is inevitable. This means financial loss; vice versa, the use of best-quality material for inferior and cheap instruments serves no purpose. This again means financial loss. In the case of optical glass this is especially true because of the many different uses to which the glass is put. In high-precision measuring instruments, such as military fire-control instruments and microscopes, the best quality glass is necessary; in low-power instruments, such as field glasses, which serve chiefly as an aid to vision, the tolerance limits are not so narrow, and less good glass may be employed; a still lower grade of glass serves the purpose adequately in cheap photographic lenses. Wherever the cost of manufacture is high, inefficient and inadequate inspection methods mean financial loss and a serious wastage and misuse of material. Proper inspection by intelligent observers is an expensive process; but in modern business effort such methods have been found by experience to pay manyfold, because they reduce losses in the final product and enable proper control to be established throughout the plant.

Experience has demonstrated that in a large organization the inspection department should be operated as a separate and distinct branch, each inspector to report and to be reponsible to the chief of the inspection branch and not to the foreman of the particular shop to which he or she may have been assigned. Unless this is done, each foreman becomes practically the judge of his own product without reference to the assembled instrument as a whole; the inevitable result is then frequent trouble between the different manufacturing departments, each department asserting and maintaining that its standards are correct and adequate. Effective organization prescribes that the responsibility for the inspection of the component parts and also of the assembled instrument or article be lodged in a single branch or department which is in a position to establish, in cooperation with the manufacturing departments, proper and ade-

quate tolerances for the several items in a given instrument and then to insist impartially upon the maintenance of the established tolerances.

The inspection of optical glass in molded, pressed, or rolled plates is an essential step in the manufacturing process, because by it the quality of the raw glass, which is used for the lenses and prisms of optical instruments, is definitely established and unsuitable glass is eliminated at the outset. The requirements, which optical glass has to meet, are stated in detail in Chapter II. These are, in brief, chemical and physical homogeneity, high transparency and freedom from color, durability, and definite optical constants. Homogeneity tests include inspection for bubbles, for stones and crystallization bodies, for pressing defects, such as feathers, folds, or laps, for striæ, and for strain. Separate tests are made for chemical durability with reference especially to the behavior of the glass on long-continued exposure to air in different climates. These tests of chemical stability are necessarily of long duration and can be applied in general only to representative samples, not to each piece. The optical constants are measured commonly on a refractometer, and rarely by the immersion method.

For purposes of inspection the glass is ordinarily furnished in plates and blocks which are ground and polished either on opposite sides (flats) or on opposite ends. Simple inspection of these plates under special conditions of illumination enables the observer to detect stones, bubbles, pressing defects, feathers, folds, and heavy striæ and cords. For the detection of fine striæ and threads, more refined methods have to be employed.

STRIÆ.

All methods for the detection of striæ are based on the fact that striæ are of different refractivity (commonly lower) from the surrounding glass and, as a result, deflect the directions of transmitted rays of light. In actual inspection work the transmitted light rays are given very definite directions so that the slightest departure from the prescribed paths results in a local difference in intensity of field illumination, thus rendering the striæ visible. The striæ not only deflect the light, but function also somewhat as a lens so that different sides of a given stria appear unequally bright, especially if observed under conditions of oblique illumination, as indicated in figs. 7*c*, 7*e*, and 58. In figure 58 the stria is represented in section as lens-shaped and the deflection of the light rays is shown in much exaggerated form; the inequality of illumination of opposite sides of a stria when obliquely incident rays traverse the field is the chief distinguishing feature of striæ. A little practice enables the observer to distinguish between striæ and scratches on the polished surface of the plate,

especially if the plate is tilted and turned during the examination. In some cases the striæ are not sharply defined and there is only a gradual change in refractivity between different parts of the plate. This gives rise to a disturbed, nonuniform, and even wavy illumination of the field which suffices to render the glass unsuitable for high precision work, but still usable for lower-grade optical systems. Poor annealing may also give rise to disturbed field illumination, especially near the edges of the plate.

There are a number of different methods available for the detection of striæ in optical glass. These may be divided into two general classes, namely, direct-vision methods and projection methods. Both types were used before the war, but not on a scale commensurate with war-time needs and conditions. It was necessary, therefore, to investigate the several different methods with reference to sensitiveness, simplicity and speed of operation, effect on eyes of inspectors, and general practicability as routine factory methods.

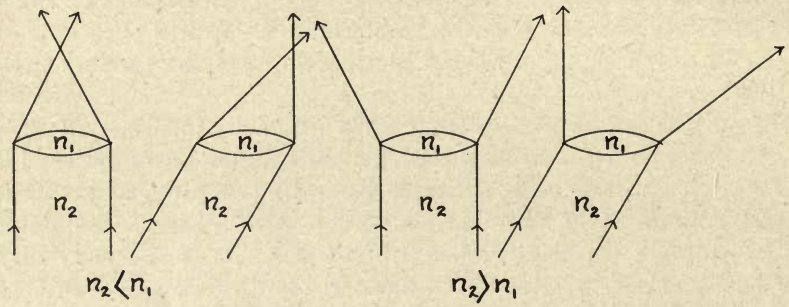


FIG. 58.—Diagrams illustrating the effect of a body, such as stria, of lenticular cross section on transmitted light rays; n_1 is the refractive index of the stria, n_2 that of the inclosing glass.

Experience proved that conditions differed greatly in different plants, and that a method acceptable to the workman in one district was by no means equally acceptable to the workman in another district.

In the inspection of optical glass, especially for striæ, the personal equation of the inspector plays an important rôle, and it is extremely difficult to devise methods which insure that the same standard quality of product is passed by different inspectors or even by the same inspector at different times. Certain inspectors, by virtue of keen eyesight and long training and experience in optical work, may detect at a glance fine striæ in plates which pass unnoticed by a less skilled inspector. It is also true that in changing from one method of inspection to another, or even from one instrument to another of similar construction, the inspector requires a certain amount of practice before his inspection becomes critical. It is, moreover, well known that heavy striæ may be present in a plate and yet escape detection if the plate is examined through one direction only.

For example, plates of rolled plate glass, which is not optical glass and is characterized by heavy ream when examined edgewise, appear to be free from striæ when inspected through the "flats." On the other hand, it is possible, in the case of ribbon striæ, that these can not be detected when the plate is examined edgewise, but they are then easily observed through the flats. The merits of the several different available methods are accordingly difficult to appraise properly, and detailed study under factory conditions is necessary before a satisfactory decision can be made.

Experience and nice discrimination are required to draw the line between glass of first quality, second quality, and cullet. In Chapter II the effects of the presence of striæ in glass in the different types of optical instruments are discussed in detail. In high-power instruments in which good resolution is required the striæ which deflect, even slightly, an appreciable number of light rays from their normal paths produce a noticeable effect on the resulting image and thereby seriously impair the efficiency of the instrument. For such instruments optical glass of the best quality is necessary and should be most carefully inspected for striæ. For optical glass intended for low-power visual instruments, less critical inspection suffices. In time of war there is a constant tendency to favor quantity in favor of quality; inspectors are inclined, as a result both of this attitude and of their inexperience, to pass much glass as first class which, after having been worked up into high precision lenses and prisms, must be discarded; also carelessly to assign much first-quality glass to second-rate glass.

The different methods in common use for rendering visible fine striæ in optical glass are illustrated in figures 59 to 64.

DIRECT VISION METHODS.

The modified Toepler method.—One of the best methods for detecting striae is a modification of that employed many years ago by Toepler for the testing of astronomical objectives. This method is illustrated diagrammatically in figure 59, in which S is a source of light, such as a concentrated tungsten filament bulb, D a diffusion screen of finely ground glass or thin opal glass, A a pinhole or narrow cross slit aperture in the rear focus of the collimating achromatic lens, L_1 (E. F. 30 to 75 centimeters and diameter 5 to 13 centimeters). The larger the diameter of the lens the better, as it furnishes a larger field. The plate to be inspected is placed at P; behind it is the achromatic field lens L_2, which in the case of 5-inch condenser lenses of long focal length may be used in combination with a second similar lens to shorten the focal lengths to 30 or 40 centimeters. At B is a movable pinhole aperture, or better, a cross slit, figure 59*a*, in the rear focal plane of the field lens. This is necessary because the surfaces on the plate may not be strictly parallel and therefore deflect and shift the light slightly. The

cross slit aperture is held in place by a small spring or clip and can be shifted at will. In practice the eye is moved until the plate to be examined appears in half shadow; in this position the striae are readily seen on tilting and moving the plate across the field. Experience has shown that ribbon striae parallel to the polished surface of the plate are not easily detected by this or any other method. Their presence is indicated by a disturbed illumination of the field, but no striae are seen as such. Plates polished on the sides enable

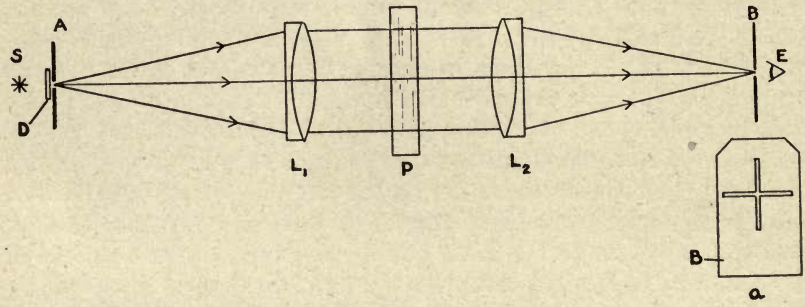


FIG. 59.—Modified Toepler method for the inspection of optical glass plates. *S* is the source of light; *D*, a diffusing screen; *A*, a small pinhole aperture; L_1, an achromatic lens; *P*, the plate under examination; L_2, an achromatic lens; *B* the cross-slit opening illustrated on a larger scale in 59*a*; *E*, the eye of the observer.

the observer to determine just where the striae are, and thus to cut out and trim off the striated portions; plates polished on the ends enable the observer to detect the presence of striae through a long glass path, but do not permit him to locate the exact position of a stria with sufficient exactness, so that the striated portion can be cut out from the plate without wasting good glass. The ideal method is to have the glass polished both on the sides and ends. Glass plates and blocks submitted for final inspection should be

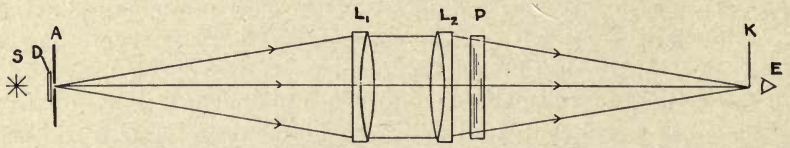


FIG. 60.—The knife-edge method for the inspection of striae in a plate of optical glass. *S*, is source of light; *D*, a ground glass diffusing disk; *A*, a pinhole aperture; L_1, an objective lens; L_2, an objective lens; *P*, a plane parallel plate; *K*, a thin metal shield (knife-edge); *E*, the observer's eye.

polished at least on opposite ends. Felt polish is satisfactory for inspection purposes.

The arrangement in figure 59 may be modified as shown in figure 60 by using well-corrected objectives and placing the plate between the rear lens and the eye, at which a knife edge or adjustable slit is used. Experience with this method has proved that it is highly sensitive, but that a considerable amount of time is lost because of the shift of the focal point; furthermore, the field covered is normally slightly

less than that obtained by the arrangement of figure 59; for practical factory operations the first device is more rapid and therefore preferable.

The concave-mirror test.—Another method to obtain rays of definite direction is to use a concave mirror, *M*, of 25 centimeters diameter and about 1 to 2 meters radius of curvature (fig. 61); to place near the center of curvature an illuminated pinhole aperture *A* and a second pinhole or cross slit aperture near *E*, and through it to view the plate placed at *P*, as indicated in figure 61. As in the first method, the presence of striae is shown by lack of uniformity in field illumination. This method is very sensitive, but has the disadvantage that the plate under inspection is 5 or 6 feet away from the observer and can not be tilted or turned and thus readily marked for the trimming off of the striated portions. It may be used, of course, nearer the observer, but the field may not then be fully covered. The principle on which

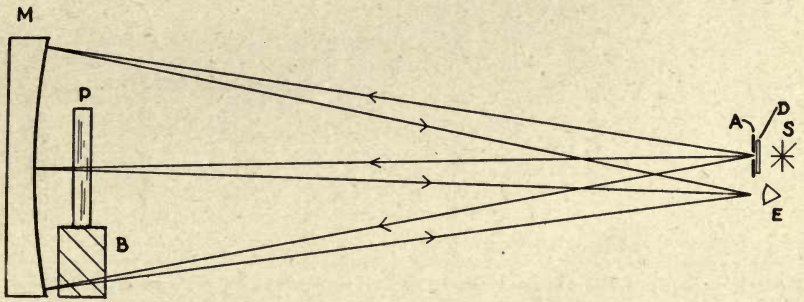


FIG. 61.—Concave mirror test for the inspection of striae in plates of optical glass. *S* is source of light; *D*, ground glass diffusing disk; *A*, pinhole aperture; *M*, a concave mirror; *P*, plane parallel plate of glass; *E*, the observer's eye.

this method is based is identical with that underlying the Toepler method for the testing of the quality of figuring of an objective lens.

The immersion method with monochromatic light.—This method was applied by Mr. W. H. Taylor, of the Bureau of Standards, at first to avoid the necessity of polishing plates for inspection. For this purpose the sides of the plates are ground flat. Each end is then covered with a thin film of a liquid of the same refractive index and this is in turn covered with a flat plate. Because of the difference in dispersion between liquid and optical glass plate a monochromatic illuminator of the type shown in figure 62 is used to facilitate the exact match in refractive index between plate and liquid. Under these conditions the ground surfaces disappear entirely and the plate can be examined critically by any suitable method for striae. This method is, of course, not so rapid as the ordinary methods, which require polished end or side surfaces, but it does avoid the polishing of the plates.

Taylor adopted later the immersion method for the examination of rough irregular chunks of glass and also of plates for striae; for the purpose he used the arrangements shown in figure 62.[1] The part M is essentially a device for obtaining monochromatic light; it can be rotated as a whole about the axis K and different prismatic colors are thus obtained. A monochromatic illuminator furnishes the simplest means of matching exactly the refringence of immersion liquid to that of the immersed block of glass; the procedure for obtaining an exact

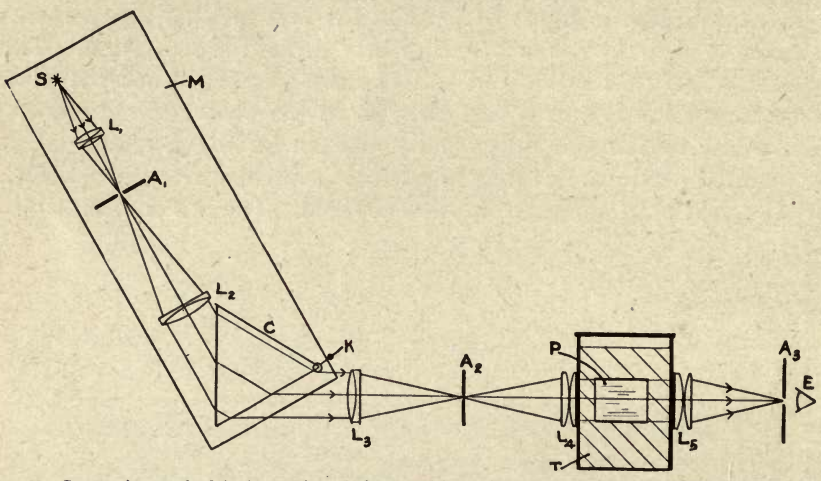


FIG. 62.—Immersion method for inspection of plates and irregular fragments of optical glass in monochromatic light as developed by Mr. W. H. Taylor. S is the source of light; L_1, a condenser lens; A_1, pinhole aperture; C, carbon sulfide dispersion prism; M, the board in which the foregoing optical parts are mounted; K, the axis about which M can be rotated; L_3, L_4, L_5, condenser lenses; T, liquid immersion tank; P, the plate or fragment of optical glass; A_2, A_3, stops; E, the observer's eye.

match is first to adjust the liquid mixture until its refractive index is equal to that of the immersed glass for some part of the visible spectrum and then to make the fine adjustment for exact match by means of the monochromatic illuminator. In figure 62, S is the source of light, a concentrated tungsten filament (electric bulb), L_1, a condenser lens, A_1, a small pinhole aperture, L_2, a collimator lens, C, a carbon bisulphide prism, L_3, a condenser lens, T, the immersion tank, fitted at opposite ends with parallel plates of plate glass and filled with the immersion liquid, L_4 and L_5, achromatic lenses, A_2 and A_3, small apertures, E, the eye. In a later arrangement the lens, L_2, is placed nearer the aperture B and the emergent rays are slightly convergent. This enables the observer to obtain approximately monochromatic light without the careful centering and adjustment required in the device of figure 62. The immersion liquids are mixtures of carbon bisulphide ($n_D = 1.628$) and benzol ($n_D = 1.501$). In place of the carbon bisulphide, α-monobromnaph-

[1] Illustrated in article on comparison tests for striae in optical glass, by L. E. Dodd. Jour. Am. Ceram. Soc., 2, 981, 1919.

thalene ($n_D = 1.658$) or α-monochlornaphthalene ($n_D = 1.633$) may be used; a commercial name for the monochlornaphthalene is halowax oil. Carbon bisulphide is unpleasant to use because of its disagreeable odor and toxic properties. Monobromnaphthalene has also an unpleasant odor and does not volatilize as does carbon bisulphide, but remains as an oily film on the inspected glass surfaces. Both

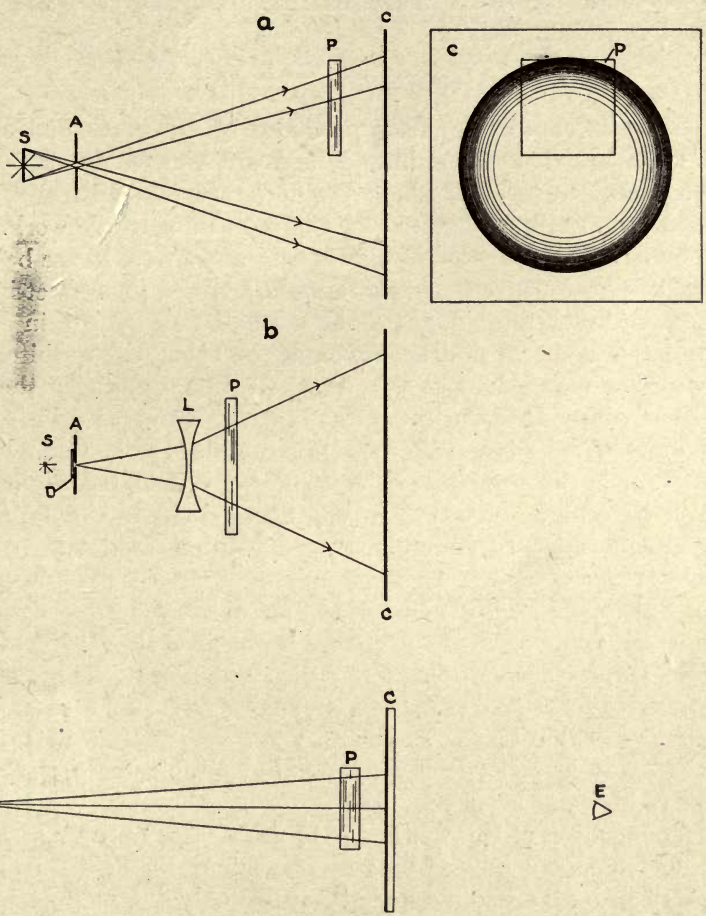


FIG. 63.—Simple projection methods for the inspection of optical glass for striae. (*a*) *S* is source of light; *A* a small circular opening; *P*, optical glass plate; *C*, projection screen. (*b*) *S* is the source of light; *A*, small aperture; *D*, diffusing disk; *L*, a dispersive lens; *P*, optical glass plate; *C*, the screen. (*c*) *S* is the point source of light; *P*, the optical glass plate; *C*, a projection screen consisting of thin white or opal glass; *E*, the observer's eye behind the screen.

liquid mixtures are not satisfactory for factory purposes and the workmen object seriously to them. The fumes induce headaches and a feeling of debility, so that it is questionable if the quality of inspection by the immersion method can be maintained at a high level. At one of the plants the men after a thorough test refused to continue work with the immersion methods. At the plant at which

the method was adopted the men showed evidences of the toxic action of the bisulphide fumes and did not maintain a high standard of critical inspection. As a laboratory method, however, the method is useful especially for the rapid measurement of refractive indices and dispersions.[2]

In the case of an accidental mixing of plates of several different types of glass, these are most readily sorted and separated by use of the immersion method.

PROJECTION METHODS.

In these methods the effects produced by the plate under inspection on a uniformly illuminated field are viewed directly or in a photograph. Several of these methods are less critical than the foregoing, but still well suited for rapid, medium grade work.

The methods illustrated in figures 63 *a* and *b* were in use before the war. In figure 63*a* an electric lamp is inclosed in a sheet-iron box with ventilating top. Light from a small hole or slit in the box illuminates a sheet of drawing paper or other even white diffuse reflecting surface a foot or two distant. The opening in the box is sufficiently large that the illuminated surface is surrounded by a fairly wide half-shaded edge. The rays illuminating the penumbra or half shadow have fairly definite directions and if deviated slightly from their normal paths give rise to local unequalities in the illumination of the penumbra. Striae under these conditions are readily detected, if heavy; and if light, can be seen after practice. If the plate be examined in the bright, nonshaded part of the field, the light is not sufficiently unidirectional to disclose slight differences of field illumination, and as a result fine striae pass unnoticed. This method is satisfactory for the elimination of heavy striae and cords. Glass which passes this test is satisfactory for field glasses and ordinary photographic lenses, but it may not be suitable for optical instruments of high precision.

A modification of this method is to use a large opening so that the half-shaded edge is present only on one side of the field. In practice it is well in both these methods to utilize only the half-shadow part of the field and to cover the otherwise fully lighted part of the field with black, matt paper. This cuts down much of the glare present in the field, which is tiring to the eyes. The use of properly colored glasses is helpful in this connection.

The method of figure 63*b* is a variation of method 63*a* and of about the same degree of accuracy. *S* is the tungsten bulb source of light; *A* a small, pinhole aperture; *L* a biconcave lens 3 inches in diameter. The rays emerging from *L* form a cone which passes through the plate *P* under inspection and impinges on the screen *C*. If the

[2] See in this connection a paper by R. W. Cheshire, Phil. Mag., 32, 409, 1916.

plate P is free from striae, the illuminated field at C is uniform; but if striae be present, they give rise to characteristic lines and threads of less or greater intensity of illumination than the rest of the field, and hence are readily detected. In this method, as in certain of the preceding methods, the plate, as viewed, is magnified two or three fold.

In the method[3] of figure 63*c*, a thin sheet of opal glass (one-fourth millimeter thick) flashed on a sheet of clear glass is substituted for the screen of method, fig. 63*a*. The shadow effects of transmitted rather than reflected light are noted on the screen. As source of light Dodd recommends a small tungsten light with small V-shaped filament helix of tungsten wire. (Edison Mazda No. 131, 6–8 volts; 3.5 amp.; c. p. 28, filament C.) An equally satisfactory source of light for this and for methods 1 to 4 is the Ediswan pointolite bulb. Dodd's work indicates that with practice this method can be used in place of the methods 1 to 4; it is evident, however, that the conditions of illumination in this method are not so critical as in methods 1 to 4 and that the method is correspondingly less sensitive.

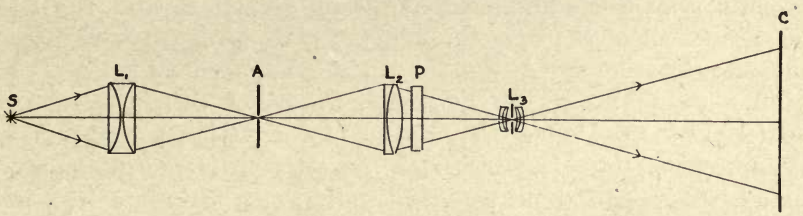


FIG. 64.—Projection method for the examination of striae in optical glass. S is the point source of light; L_1, a condenser lens; A, pinhole aperture L_2, an objective; P, optical glass plate; L_3, projection lens; C, projection screen.

The method of figure 64 was used by T. T. Smith[4] and others for photographing striae in plates of optical glass. As indicated by the figure a special optical system was adopted and favorable conditions were thereby attained for the detection of striae. If for the photographic plate a diffusing screen or a thin plate of opal glass is substituted, this arrangement is satisfactory for the visual detection of striae. In figure 64, S is the source of light, such as a concentrated tungsten filament or pointolite bulb, L_1 a condenser lens system, A a small aperture, L_2 a collecting lens, P the glass plate, L_3 a photographic lens, and C the photographic plate or screen.

In all projection methods the tiring effect of glare on the inspector's eyes should be reduced by proper attention to the arrangement and intensity of the light source and especially to the reflecting or transmitting screen[5] on which extremes in contrast of light intensity should be avoided as much as possible.

[3] L. E. Dodd, Jour. Am. Ceram. Soc., 2, 977, 1006, 1920.

[4] T. T. Smith, A. H. Bennett, A. E. Merritt, Bureau of Standards, Scientific Paper No. 373, 1920.

[5] An undeveloped photographic plate is a satisfactory screen for this purpose. In the course of time it becomes dark and should be replaced by a fresh plate. Light buff colored smooth drawing paper commonly used.

Practical tests of the majority of above methods led to the adoption of the first method as best adapted to the routine inspection of glass plates, polished either on the ends or on the sides (flats). Most of the glass accepted by the Army and Navy inspectors was inspected by this method, and the results obtained proved its usefulness. The method had become standard even before the war, the only change introduced by the writer being the cross slit. (Fig. 59*a*.)

In routine work with the first method there are several precautions to be taken which are essential to rapid, critical inspection. The source of light should not be too strong. A 40-watt tungsten bulb is adequate. In front of the small aperture A a small ground glass or thin opal diffusion plate is introduced in order properly to illuminate the aperture. In place of the diffusion disk a condenser lens, as in figure 64, may be used to image the point source of light in the aperture, but the diffusion disk is perfectly satisfactory and simpler than the condenser lens arrangement. The aperture A should be located at the focus of the achromatic lens L_1. It is essential that this adjustment be carefully made because the degree of parallelism of the rays through the plate P depends directly on the exact location of A. The simplest method for testing the position of A is to sight through the lens L_1 toward A with a telescope or field glass focused on a very distant object; A is then moved until it appears in sharp focus through the telescope. Lens L_2 is set up parallel to L_1 and about a foot distant. The position of the cross-slit aperture B is located at the position of sharp focus of the aperture A. In the normally adjusted instrument the center of the aperture cross B coincides with the small image spot of A. A shield is commonly placed in front of D to cut off stray light from the light S; the observer should be, moreover, shielded from direct skylight. Total darkness is not necessary nor advisable; the eye functions best and with least fatigue if it is not exposed to strong contrasts in illumination.

A plate which is to be examined for striae is first inspected for cleanness of polished surfaces. The plate should reach the inspector in clean condition; if it is not clean, he should return it for cleaning; it is not his function to clean plates. He should, however, dust off each plate with a soft cloth before critical inspection.

The clean plate is placed in the position indicated in Fig. 59 between the two lenses L_1 and L_2; the observer's eye views the plate through the slit aperture B. The eye is placed as near as possible to this aperture in order to receive light from the entire surface of lens L_2. The opposite surfaces of the plate P are rarely strictly parallel, with the result that there is a perceptible shift of the point of focus at B. The plate is accordingly turned about the horizontal axis, its surfaces still remaining approximately parallel with the

flat lens surfaces, until the focus crosses one of the slit openings, and the plate and field in consequence appear brightly illuminated; the plate is then rotated a little farther and appears in half shadow or practically dark. In this position striæ are most readily detected and with practice can be seen at a glance. At first the inspector may experience difficulty in locating the positions of half shadow; but after a few trials his eye becomes accustomed to the phenomena and he is able to turn the plate without special effort to a sensitive position.

In case the plate under examination is ground and polished on the flats, the striated areas are marked with colored wax crayon on the plate to be trimmed away by the trimmers.

Scratches on the flat surfaces may be deceptive at first, but after short practice they are readily distinguished from striæ.

A slight difference in illumination between different parts of the field in which no striæ are recognizable, occurs in some plates and is commonly indicative either of fine or ribbon striæ so placed that they are not visible when viewed in the direction of observation, or of a gradual change in refractive index from one part of the plate to another. A plate, exhibiting these phenomena, should be inspected through another direction before acceptance. In an occasional plate a curious, concentric system of rings can be seen; these are marks left by the grinding or polishing tool, the plate having been rotated for an appreciable period of time about the center of the concentric rings as axis.

Experience has shown that for critical work of the highest precision inspection through one direction only does not suffice; the plates should be inspected through different directions to insure freedom from striæ. For most purposes, however, critical inspection through one direction suffices to eliminate most of the striæ.

Bubbles, seeds, stones, crystallization bodies; pressing defects, feathers, folds, laps.—A plate of optical glass after having passed inspection for striæ is examined for "seeds," "stones," and "feathers and folds." These defects are most readily observed under conditions of illumination, approaching those of dark-ground illumination; these are readily obtained by placing a source of light (electric bulb) under a cardboard or wood cover (fig. 65), thereby screening off all but horizontal rays of light. This arrangement is analogous in its effects to a ray of sunlight which, streaming into a room, renders visible the minute dust particles in the air; foreign particles in the glass, such as minute seeds or stones serve to reflect and diffract the impinging light rays, so that they reach the eye of the observer; each particle, thus illuminated, appears as a bright source of light or a star and is readily visible. In order that the contrast between light and dark be as great as possible, the plate under

examination should rest on a sheet of dull black paper or a piece of black felt or cloth and be shielded from light at the sides; the background is then dark and the brightly illuminated points stand out clearly.

The presence of a small number of bubbles in a plate of optical glass is not sufficient cause for its rejection. All stones and crystallization bodies, also feathers and folds, should be removed either by grinding or sand blasting, if near the surface, and by chipping out, if deeply buried. The presence of a stone or fold or feather in a lens or prism is adequate reason for rejection.

Inspection for strain.—Two factors are important in the inspection for strain, namely, the maximal amount of strain in a plate and the general distribution of the strain. Strain in optical glass is readily recognized by the effect which a strained piece of glass exerts on plane-polarized light waves during transmission. In a strained piece of glass, waves of light are transmitted with different speeds, depending on the direction of transmission and on the plane of vibration.

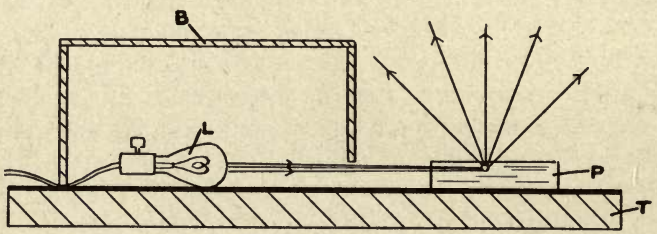
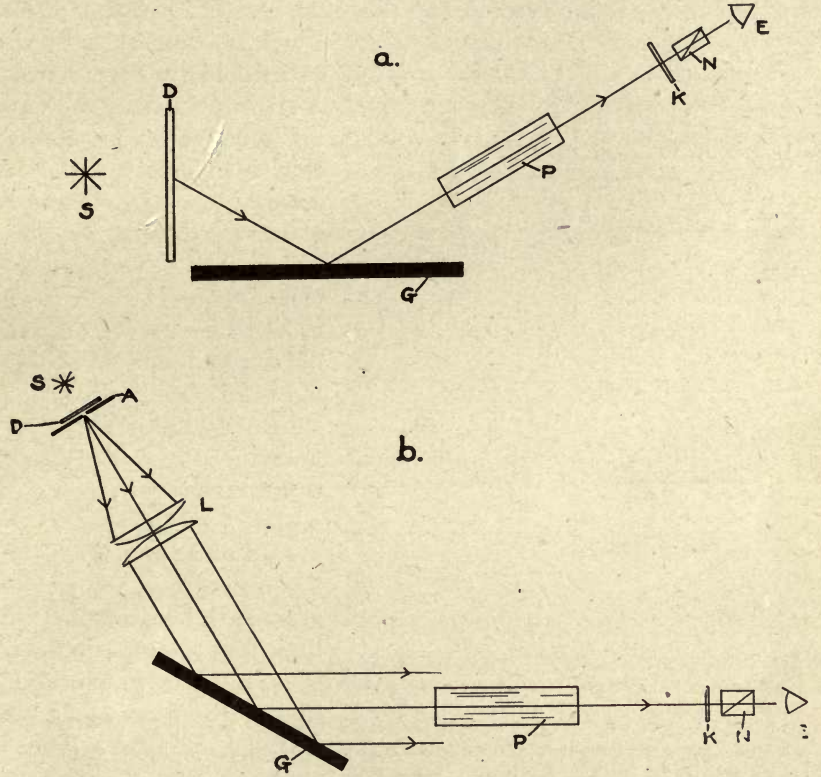


FIG. 65.—Arrangement suitable for the inspection of glass plates for bubbles, seeds, stones, and pressing defects, etc.

This gives rise to the phenomena of double refraction which can be recognized between crossed nicols by the interference colors which are formed and whose sequence is practically that of the Newton color scale. The particular interference color formed depends directly on the distance between two interfering light waves; this distance in turn depends both on the difference in speeds of the two interfering waves through the strained glass (stresses in the glass) and on the length of the glass-path. A definite and yet easily attainable limit of strain even under war-time conditions of annealing was accordingly set and expressed either in terms of absolute birefringence for a specified color or in terms of path difference per centimeter glass-path. This war-time limit is that of the maximum observable strain in a plate and is, for sodium light, 20 millimicrons path-difference per centimeter glass-path at the margins or 10 millimicrons path difference at the center of the plate; expressed in birefringence these limits are $20 \cdot 10^{-7}$ and $10 \cdot 10^{-7}$, respectively. The distribution of the interference colors should, moreover, be symmetrical in the plate. A more severe and yet easily attainable tol-

erance limit is half the above or maximal path difference of 10 millimicrons per centimeter glass-path at the margins of the plate; this corresponds to a path difference of 5 millimicrons at the center of the plate and may be considered to be a normal and reasonable peacetime tolerance.

The practical utilization of these limits is extremely simple. Apparatus arranged as in figure 66*a* or figure 66*b* is serviceable. In figure 66*a*, *S* is the source of light (electric bulb), *D* a piece of



IG. 66. Apparatus suitable for the inspection for strain in optical glass plates. In fig. 66*a* a diffusing screen of ground glass illuminated from the rear by an electric lamp is used; in fig. 66*b* the diffusing screen is replaced by a condenser lens system. In both arrangements the lamp is properly housed in a sheet-iron box. (*a*) *S* is the source of light; *D*, a diffusing screen of ground glass; *G*, plate of opaque glass; *P*, optical glass plate; *K*, sensitive-tint plate; *N*, nicol prism; E, observer's eye. (*b*) D, diffusing plate; *A*, pinhole aperture; *L*, condenser lens; *S*, *G*, *P*, *K*, *N*, and *E*; are the same as in (*a*).

ground glass, *G* a polished plate of opaque glass so tilted that the angle of incidence is the Brewster polarizing angle (tangent of the angle is equal to the refractive index of the glass). For ordinary opaque glass $n = 1.52$, and therefore the polarizing angle is 56° 40′. This position of the polarizing plate is readily found even without angular measurements by observing through a nicol the light reflected from the plate inclined at different angles to the line of sight. At the polarizing position the field is practically dark because the

reflected light is practically plane-polarized and is extinguished by the analyzing nicol. Figure 66*b* is similar to figure 66*a*, except that the parallelism of the rays incident on the plate *G* is insured by the use of a point source of light (pointolite bulb or concentrated tungsten filament) at the rear focus of a condenser lens. Either apparatus functions satisfactorily for the purpose.

To render the low, first-order interference colors more readily apparent a sensitive-tint plate of selenite, or of quartz, or as a last resort, of mica, is inserted in the diagonal position in front of the analyzer, thus coloring the entire field a uniform purple. A slight change in the path difference suffices to change this interference color to orange if the path difference is decreased, or to blue if it is increased. The sensitive tint is observed between crossed nicols when the path difference, in air, for sodium light is 555 millimicrons. A shift of 10 millimicrons suffices then to cause a perceptible change in color. In a plate 10 centimeters wide a path difference of 20 millimicrons per centimeter glass-path becomes 200 millimicrons total path difference; in other words the interference color along the margins of the plate is changed from the sensitive purple tint to bright yellow or greenish blue; the center is then orange yellow or blue, depending on the position of the plate. The observed phenomena are indicated in figures 67 *a*, *b*, *c*, *d* and 10 *a*, *b*, *c*, *d*, *e*, *f*, *g*.

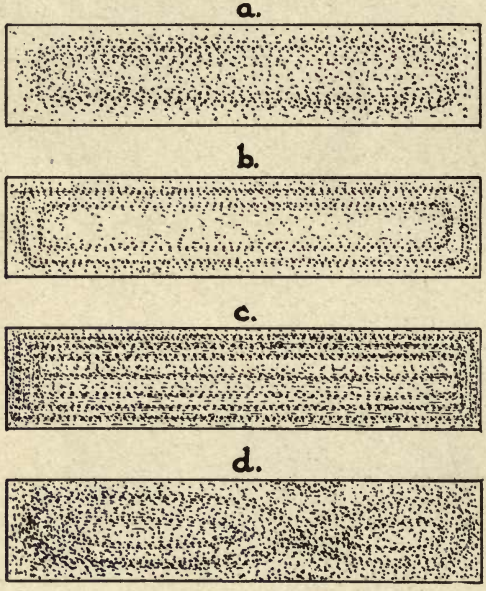


FIG. 67.—Illustrating the appearance of the four grades o annealing in optical glass plates, 10 centimeters long, when viewed in polarized light with the aid of a sensitive-tint plate through the ends. (*a*) Annealing excellent; (*b*) annealing fair; (*c*) annealing poor; strain evenly distributed; (*d*) annealing poor, strain unevenly distributed. The curves in these figures represent simply different interference colors (Newton color-scale) as they are observed with the aid of a sensitive-tint plate; thus in fig. 67*a* the interference colors may pass from blue at the margin of the plate to purple and magenta (sensitive-tint) to red and reddish orange at the center. In the other figures the range of interference colors from center to margin of the plate is still greater.

It should be noted that a very large percentage of the glass passed by Government inspectors during the war period was so well annealed that the resulting maximum path difference was less than 10 millimicrons per centimeter, or 5 millimicrons at the center of the plate.

Once the polarization apparatus is set up the inspector examines three or four plates at a time. Each plate is examined through the

edges; polished edges are not required. The plate is inserted in the line of sight in the diagonal position or so that its edge includes an angle of 45° with the plane of incidence of the reflecting opaque polarization plate G. A plate which shows distinct green or yellow interference colors is rejected and returned for reannealing. Acceptable are plates which show changes in color ranging from orange red or red to purple to blue and in these the color changes must be symmetrical with reference to the outline of the plate.

Experience has demonstrated that, although for the exact measurement of path differences a graduated quartz wedge or Babinet compensator or other sensitive device is necessary, the above simple apparatus is entirely satisfactory for routine factory inspection.

The design and construction of both the striæ and the strain inspection apparatus should be so carried out that the inspector can work with a maximum degree of comfort and with the least expenditure of energy in lifting and transferring the plates. Strained positions should be avoided because they tire an inspector and reduce at once his efficiency.

The transparency of the plates.—The inspector is commonly not required to determine the degree of transparency of optical glass plates. This is, however, an important factor and may well be considered briefly in this section. The methods employed are those of the physical laboratory, modified slightly with reference to the problem of light-transmission in optical glass. A number of different instruments can be used for the purpose; they are photometers and, as such, depend on the ability of the observer to match or balance two contiguous, illuminated fields. Under favorable conditions of illumination it is possible to detect differences of 2 and even 1 per cent in the intensity of illumination between the halves of a photometric field.

In measurements of the amount of light transmitted by a plane-parallel plate, account must be taken of the light lost by reflection at the plane surfaces. Let ρ be the amount of light reflected at each boundary surface. Let β be the amount of light transmitted per unit thickness (1 centimeter) of plate; then $1-\beta$ is the amount absorbed per unit thickness. For a thickness l the amount of light transmitted is β^l. If multiple internal reflection be taken into account, the amount, I, of light transmitted by a plate of thickness l, is

$$I=\beta^l(1-\rho)^2(1+\beta^2\rho^2+\beta^4\rho^4+\text{----})=\frac{\beta^l(1-\rho)^2}{1-\beta^{2l}\rho^2}.$$

From this equation we find

$$I\rho^2\beta^{2l}+(1-\rho)^2\beta^l-I=0.$$

If in this equation the value of ρ, as stated by the Fresnel equation for the intensity of reflected, vertically incident light, namely, $\rho=\left(\frac{n-1}{n+1}\right)^2$, in which n is the refractive index of the glass, be substituted, we find

$$(n-1)^4 I\beta^{2l}+16n^2\beta^l-I(n+1)^4=0,$$

a quadratic equation in β^l in which n and I are known. The equation is, however, based on the assumption that Fresnel's equation is correct. Experiments with glass plates have proved that the amount of light reflected by a glass surface can be appreciably reduced by short exposure of the polished surface to certain solutions. It is advisable, therefore, to eliminate ρ from the equations by measuring the transmission on different thicknesses of the glass plate.

The first equation can be written for two different thicknesses l_1 and l_2 of the plate

$$\beta^l{}_1(1+I_1\beta^l{}_1)\rho^2-2\beta^l{}_1\rho+\beta^l{}_1-I_1=0$$

$$\beta^l{}_2(1+I_2\beta^l{}_2)\rho^2-2\beta^l{}_2\rho+\beta^l{}_2-I_2=0$$

From these two equations ρ can be eliminated. In the resulting equation, I_1, I_2, l_1, and l_2 are known, so that the value β can be ascertained. The resulting equation is, however, so complicated that in general the roots can be obtained only by approximation methods. A direct and simple approximate solution can be obtained by neglecting ρ^2 in equation (1); in this case we find for two transmissions I_1, I_2, measured on thicknesses l_1 and l_2.

$$\frac{I_1}{I_2}=\frac{\beta^l{}_1}{\beta^l{}_2} \text{ or } \beta=\left(\frac{I_1}{I_2}\right)^{\frac{1}{l_1-l_2}}$$

The value of β computed from this equation is too low; but it is of the correct order of magnitude.

If internal reflections be neglected, the ratio of the measured transmissions or the two thicknesses is the transmission for the path l_2–l_1. The practical effect of neglecting ρ^2 is therefore to neglect the internal reflections; but these add at most only 0.1 to 0.3 per cent to the transmitted light. To disregard these in the equations is to obtain too high a transmission and hence too small an absorption. In the case of a thick plate of relatively high absorption this error is not great; but in the case of a thin plate of high transparency the percentage error may be appreciable.

The above relations show that, in case results of greater accuracy are desired, the only feasible method is to measure the amount of light reflected at vertical incidence. The difference between the original intensity and this reflected amount combined with the amount transmitted gives directly the amount absorbed by the plate.

By measuring the intensity ratios for two thicknesses of plate, and by placing each thickness of plate in front, first of the prism set of the photometer and then in front of the second aperture of the photometer, the observer avoids the difficulties arising because of

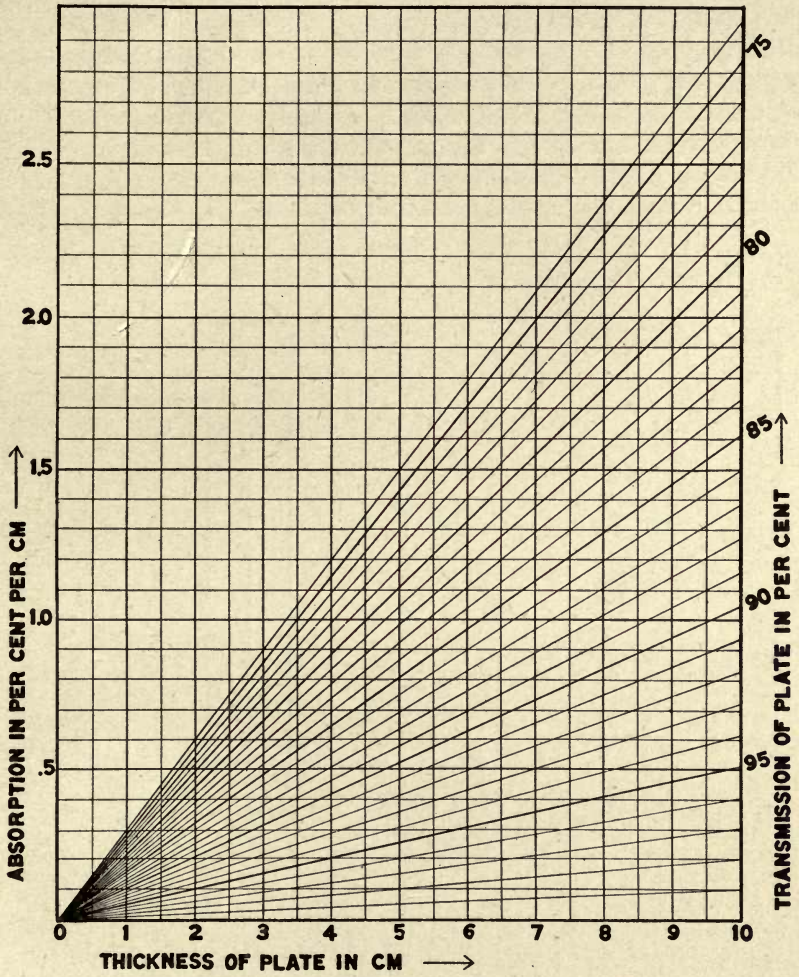


FIG. 68.—Graphical solution of the equation for light-transmission of plane-parallel plates. The abscissae represent the thickness of the plate in centimeters; the radiating lines, the percentage transmission of the glass plate; the ordinates, the absorption in per cent per centimeter glass-path.

reflection at the boundary surfaces of the glass plate and because of the decreased field intensity ratio resulting from the prism set.

The transmission β for a plate of unit thickness can be ascertained from the last equation which may be written

$$\log \beta = \frac{1}{l_2 - l_1} \log \frac{I_1}{I_2}$$

In figure 68 a graphical solution of this equation is given; the abscissae represent the thickness of the plate in centimeters. the ordinates the absorption in per cent per centimeter glass-path, and the sloping lines the percentage transmission of the plate.

During the war there were used for the measurement of the light transmission of optical glass plates and of optical instruments three different types of photometers, namely, a bench photometer, a photometer with neutral tint wedges, and a polarization photometer. In the bench photometer[6] (fig. 69) two similar electric bulbs, S_1, S_2, serve as light sources and are wired on the same circuit; each light illuminates an opal glass plate and these are viewed together by means of a photometer prism-set and eyepiece. The lamp S_2, of part

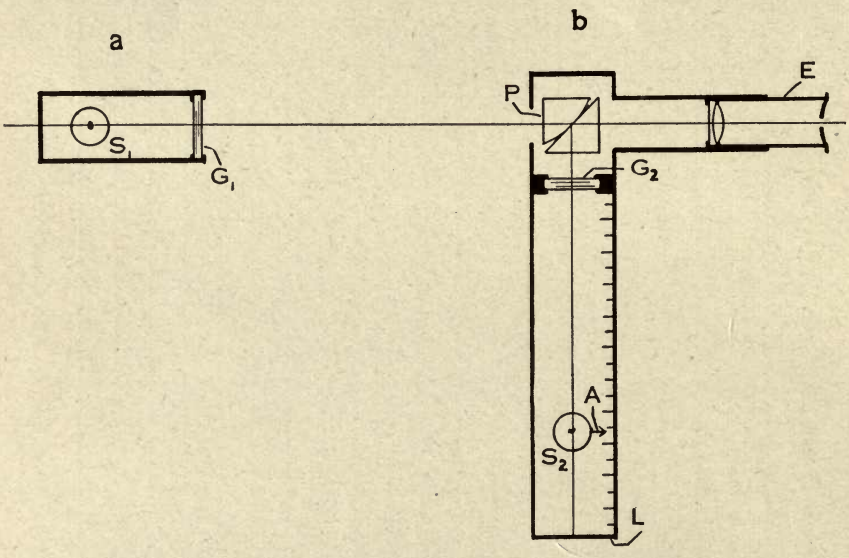


FIG. 69.—Apparatus for the measurement of the light transmission in optical glass plates. S_1 and S_2 are electric lamp bulbs; G_1 and G_2, thin plates of milk glass; P_1, a Lummer-Brodhun photometer prism; L, graduated scale; A, position indicator for the lamp S_2; E_1, eyepiece. Designed and manufactured by Keuffel and Esser.

b, can be moved along a graduated scale L and its distance a from the opal plate G_2 at any position can be read off directly. The fields are brought to uniform illumination throughout and the position of lamp S_2 is recorded. The glass plate is then inserted between the parts a and b; the field is again brought to uniform intensity and the position of S_2 recorded (distance a_1). The percentage transmission is then a_1^2/a^2. With this instrument in proper adjustment the light transmission can be measured to about 1 per cent.

In place of the optical bench with a sliding lamp, a photometer with graduated neutral tint wedges may be used and sighted toward a uniformly illuminated field. A device of this nature (fig. 70) was

[6] Designed and constructed by Keuffel and Esser, Hoboken, N. J.

constructed during the war in the Geophysical Laboratory and proved to be satisfactory. The details are illustrated in figure 70; W_1 and W_2 are carefully graduated neutral tint wedges,[7] P_1 and P_2 right angle reflecting prisms; L_1, L_2, objective lenses; A_1, A_2, diaphragms at rear foci of L_1 and L_2, respectively; P, the reflecting eyepiece prism consisting of two right angle prisms cemented, as indicated, by optical contact; E, a positive eyepiece. A white uniform source of light is obtained by means either of a white diffusing screen of magnesia illuminated by two electric lamps from the sides, or of a box lined with white paper and illuminated by electric lamps properly placed, or of a cylinder of white drawing paper illuminated at one end by a strong electric lamp and closed at the other by a piece of white Belgian opal glass with matt ground surfaces. The halves of the photometric field are first balanced without the glass plate and then

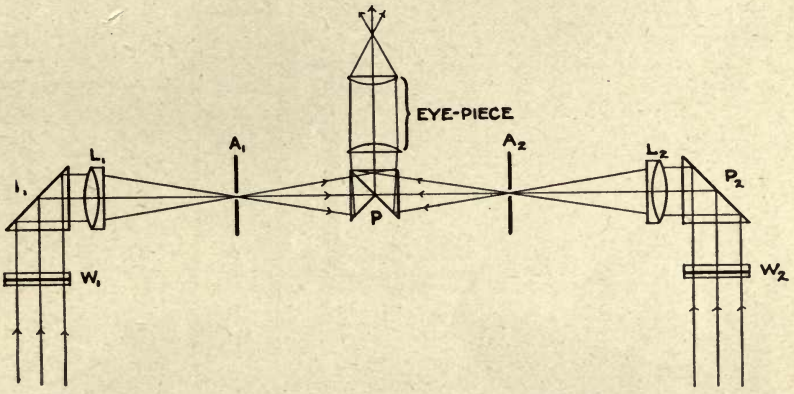


FIG. 70.—Photometer with neutral tint wedges for the measurement of the light transmission in optical glass plates. W_1 and W_2 are graduated neutral tint wedges; P_1, P_2, reflecting prisms; L_1, L_2 objective, lenses; A_1, A_2, removable stops; P, photometer prism.

after the plate has been inserted in front either of W_1 or W_2. The wedge readings give then directly the percentage ratio of the light transmitted through the plate.

A third type of photometer is the small Koenig-Martens hand polarization photometer. This was adapted to the purpose by the special attachments shown in figure 71, which were constructed in the Geophysical Laboratory.[8] These served for a large series of measurements and proved to be exceedingly useful. The optical arrangement of the photometer is shown in figure 72a. Its essential feature is the Wollaston cube, W which consists of two calcite prisms so cut that the optic axis in each prism is parallel to the end surfaces of the cube, so that, when cemented together along the sloping surfaces, the optic axis of the first prism-half is at right angles to the optic axis of the second. The effect of the prism is to

[7] Supplied by the Eastman Kodak Co.
[8] F. E. Wright, Jour. Opt. Soc. America, 2-3, 65-75, 93-96, 1919.

produce two divergent beams of plane-polarized light polarized at right angles, the first to the second. These are reduced to a common plane of vibration by the analyzer N. The intensity of each beam of light, as observed through the analyzer, is proportional to the square of the cosine of the angle α which its plane of vibration includes with the plane of vibration of the analyzer; at each instant, therefore, the intensity of the one field, I_2, is proportional to $\cos^2 \alpha$, that of the other, I_1, to $\cos^2 (90° - \alpha) = \sin^2 \alpha$; the ratio of the intensities is $\frac{I_1}{I_2} = C \cdot \tan^2 \alpha$. The constant C in this equation is the ratio of intensi-

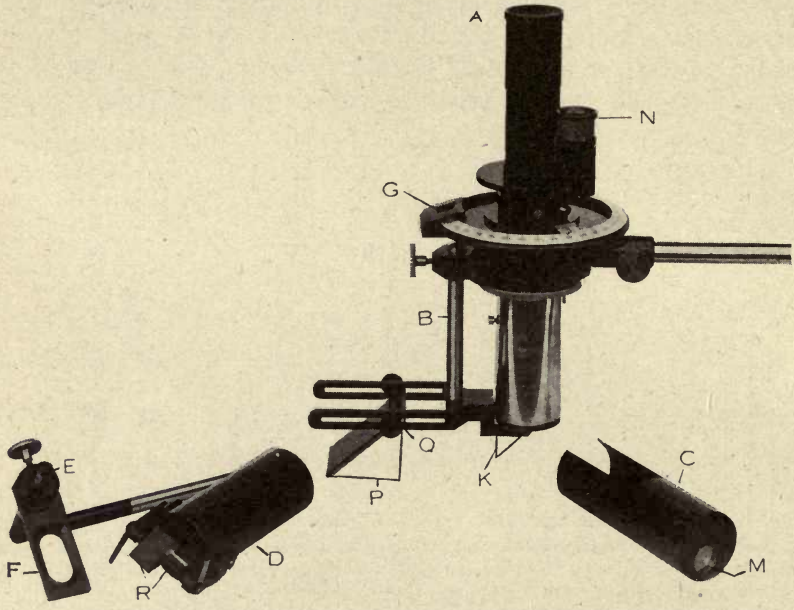


FIG. 71.—The Koenig-Martens hand photometer with special attachments for use in measuring light transmission of optical glass plates and optical instruments. *A*, the photometer; *N*, a scale-reading lens; *B*, an attachment supporting the two reflecting prisms, *K* and *P*; *C*, a tube with eccentrically mounted lens *M* for use in measuring light transmission in optical instruments; *D* and *E*, attachments used in measuring the amount of normally incidentlight reflected from a polished glass surface.

ties of the two beams of light emerging from the Wollaston cube. This ratio is approximately equal to unity. An extended series of computations shows that for a Wollaston prism of slope angle 45°, $C = 1.0026$ in case the two end faces are protected by glass slips cemented to the prism with Canada balsam ($n = 1.540$); for the bare Wollaston prism $C = 1.0006$. It is, therefore, permissible in this type of prism to consider that $C = 1$ and

$$\frac{I_1}{I_2} = \tan^2 \alpha$$

The error made by this assumption is negligible. In every instrument, however, the validity of this assumption should be tested and the value of C ascertained from the angular position α of the analyzer for which the two halves of the field are equally illuminated.

In this photometer the light enters the entrance pupils A and B (fig. 72a); these apertures are in the rear focal plane of the lens C cemented to the Wollaston prism W; the rays of light pass from the Wollaston prism through the biprism F whence they pass as parallel beams of light through the analyzer N and the eyepiece lens D, and through the exit pupil at E.

In order to separate the two apertures (entrance-pupils) of the photometer, two reflecting prisms, P, K, (fig. 71) are commonly employed. For this purpose the attachment shown in figure 71 was constructed. It is attached directly to the instrument. The large prism P slides in the grooves indicated in the figure and can

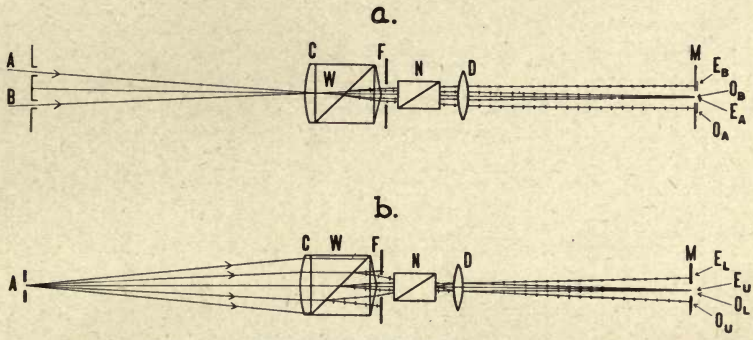


FIG. 72.—Optical arrangements of Koenig-Martens photometer. In fig. 72a the paths of the rays from the two apertures A, B, are shown; in fig. 72b the paths of the rays when only one aperture, A, is employed.

be rotated about the axis at Q. The presence of these prisms decreases the intensity of the one field and the position of equal intensity of the two halves is no longer at 45° but at a different angle α_0.

The procedure in measuring the transmission of a plate is briefly:

1. Ascertain position (α_0) of analyzer for equal intensity of fields when no plate intervenes.

2. Place plate on flat side (thickness l_1) in front of prism set and read α_1, position of analyzer for equal intensity of fields.

3. Place plate on end (thickness l_2; $\alpha_2 < \alpha_1$) and read new position of analyzer for equal intensity of the two fields (the angle α_2; $\alpha_2 < \alpha_1$).

4. Place plate on flat side in front of second aperture of photometer and read α_3, position of analyzer for equal intensity of fields.

(5). Place plate on end and read α_4, ($\alpha_4 < \alpha_3$) the position of analyzer for equal intensity of the two halves of the field. For each position take 10 readings.

The transmission for a plate of thickness $l_2 - l_1$, is then

$$I = \tan^2\alpha_2 . \cot^2\alpha_1, \ (\alpha_2 < \alpha_1)$$
$$I = \tan^2\alpha_4 . \cot^2\alpha_3, \ (\alpha_4 < \alpha_3)$$

The transmission β for a plate of unit thickness can be ascertained from the standard equation which may be written

$$\log \beta = \frac{I}{l_2 - l_1} \cdot \log \frac{I_1}{I_2} = \frac{2}{l_2 - l_1} (\log \tan \alpha_2 + \log \cot \alpha_1)$$

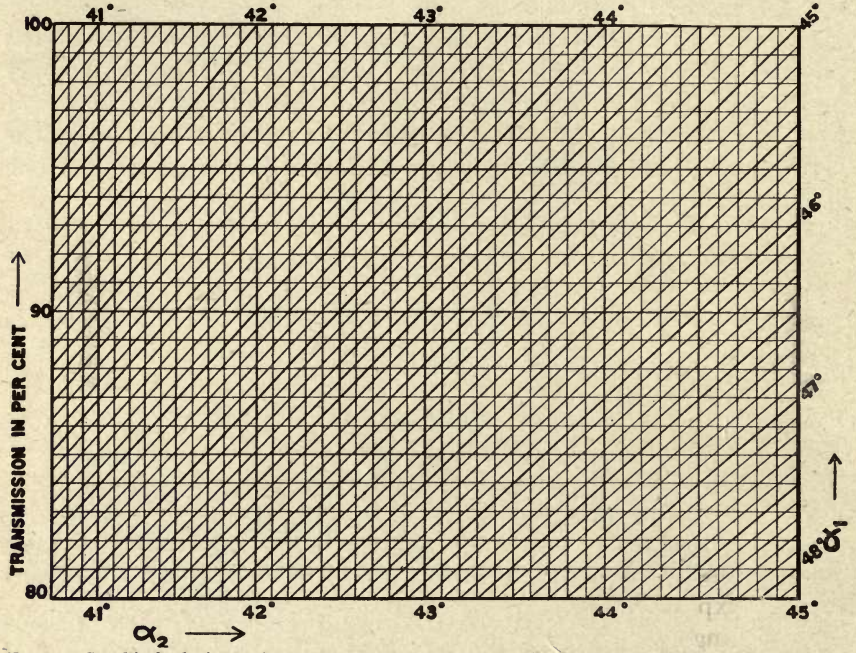


FIG. 73.—Graphical solution of the equation $I = \tan^2\alpha_2 \cot^2\alpha_1$ used in connection with the polarization photometer. The abscissae represent the angles α_2; the sloping lines, the angles α_1; and the ordinates, the percentage light transmission, I.

In case only one thickness of plate is available the reflection formula of Fresnel for vertical incidence may be assumed to be valid, and the equations are

$$\frac{I_1}{I_0} = \tan^2\alpha_0 \cdot \cot^2\alpha_2 \cdot \frac{n^2+1}{2n}$$

$$\frac{I_1}{I_0} = \tan^2\alpha_4 \cdot \cot^2\alpha_0 \cdot \frac{n^2+1}{2n}$$

$$\frac{I_1}{I_0} = \tan\alpha_4 \cdot \cot\alpha_2 \cdot \frac{n^2+1}{2n}, \quad (\alpha_4 < \alpha_2).$$

In case the amount of light ρ reflected from a single surface has been measured, the value of β can be computed from the quadratic equation on page 210.

Experience has shown the graphical solution of these equations as represented by figure 73 is adequate for all purposes; in this diagram the vertical lines are the angle α_2, the sloping lines the angle α_1, and the horizontal lines the transmissions, which, when α_1 and α_2 are given, can be read off directly. In this diagram only a limited range of angles is given, but for all optical glasses it suffices. A second diagram of the same character was also prepared, giving a much larger range and was used in the measurement of the light transmission of certain optical instruments and of experimental glasses of appreciable absorption.

Reflection of light.—In order to test the validity of the Fresnel equation for reflected, vertically incident light, and also to ascertain the effect of certain solutions in reducing the amount of light reflected, an attachment was used on the Koenig-Martens photometer which proved satisfactory and simple in operation. The attachment is illustrated in figure 71, *D* and *E*. It consists of two right-angle prisms *R*, each rotatable about a horizontal axis. Mounted back of each prism is a lens *A*, the function of which is to image the reflecting surface, held by the mount *D*, figure 71, in the image plane of the eyepiece. The cylindrical mounting for the prisms and lenses slips over the end of the Koenig-Martens photometer to such a position that the apertures of the photometer are located at the rear focal planes of the two lenses. This insures the entrance of parallel rays into the prisms. In practice the glass plate is placed on the mount *E* at *F* at such a position that its reflecting surface is seen in the field of view. The light reflected by the plate in this position is not strictly vertical, but it is so nearly so (within 10° or less) that no appreciable error is made by assuming strict verticality; this is evident from the general Fresnel expression for the intensity of rays of light reflected at different angles of incidence.

In the practical measurement of the intensity of reflected light it is convenient first to balance the fields with the reflecting surface in front of the aperture at the right side of the photometer and then to shift to the left side by rotating the prisms each through 90° and to match the fields again. By this method the first values are checked against the second. It is also advisable to mount the photometer at some distance from the source of uniform light in order that local differences of illumination may be eliminated. The uniformity of illumination of the two fields should be tested by observing the fields when both prisms are pointing directly toward the source of light, and also when they both point at the reflecting surface. By this method the intensity ratio *C* of the two fields under conditions of the same uniform incident illumination is obtained.

For this purpose the attachment of figure 71 *C* was used. It consists simply of a lens mounted at the end of a cylinder which slips over the end of the Koenig-Martens photometer. The lens is so placed that its rear focal plane falls on the aperture of the photometer, thus insuring the entrance of parallel light into the instrument. The optical instrument, whose transmission is to be measured, is placed so that its entrance or exit pupil is imaged by the lenses *F* (figure 72) and *C* (figure 71) in the image plane of the eyepiece. It is immaterial whether the exit or the entrance pupil of the optical instrument is used. In the case of telescopes the entrance pupil (objective end) is more convenient to use because it is much larger. The two fields are first balanced with the analyzer at α_1 without the optical instrument in the path; after which the instrument is placed in the path and the fields are again balanced at a_2. The transmission ratio is then

$$I=\frac{I_2}{I_1}=\tan^2\alpha_2\cot\alpha_1,\ (\alpha_2<\alpha_1).$$

The transmission can then be read off directly on the graphical plot, figure 73.

THE WEATHER STABILITY OF OPTICAL GLASSES.

An essential requirement for optical instruments intended for field use is weather stability or unchangeability of the surfaces of the lenses and prisms when exposed to the action of the atmosphere. Glass which is not stable is attacked by atmospheric agencies, such as water vapor, carbon dioxide gas, etc.; by finger perspiration and by bacteria and minute plant organisms, which eat into the finely finished optical surfaces. These agencies destroy the polish, and, in many instances, produce a film over the surface which greatly reduces the light transmission and in extreme cases may render the instrument useless.

Many methods have been devised for the purpose of testing the weather stability of optical glass. The procedure generally followed is to carry out a series of laboratory tests under definitely controlled conditions on standard glasses of known composition and of known degree of weather stability and to ascertain their behavior toward pure water and also alkaline, acid, and saline solutions of definite concentrations and at definite temperatures; from data of this nature, the probable weather stability of an unknown glass may then be inferred from its behavior in the standardized laboratory tests. There is, of course, danger in this procedure that any inference drawn from the behavior of a complex solution, such as glass, at high temperatures and possibly high pressures toward reagents of

high concentration, may bear no relation whatever to the behavior of the glass toward atmospheric agencies which are dilute agents that attack slowly and at room temperatures. The process is one of decomposition or selective solution and the behavior of the silicate system at low temperatures toward chemically weak atmospheric agents working over long periods of time does not necessarily bear any direct relation to the behavior of the same system at high temperatures and high pressures toward other reagents of much greater concentration operating for only a short period of time.

A long series of experiments by Mylius [9] and Foerster [10] bear out these statements and prove that changes in temperature produce very large differences in the ratios of alkalies to silica dissolved as well as in the total quantities dissolved; also that changes in concentration of the attacking solutions have a pronounced effect. These researches were carried out especially to test the quality of chemical glassware; but in view of the fact that weather stability means in large part resistance to attack by water at ordinary temperatures the results obtained are indicative of the relative durability of the glasses when exposed to atmospheric agencies. The lack of resistance to attack by atmospheric agencies finds expression in an optical glass surface in the formation of films, either liquid (in the form of drops ranging in size from microscopic to easily visible drops) or of crystallized aggregates (commonly as alkali carbonates); or of organic growths (algae, bacteria). The surface may become pitted and corroded; it may absorb water and swell, and then devitrify, thereby causing the surface ultimately to flake and crack; isolated spots and specks may appear on the surface, especially in the heavy flint glasses. These phenomena were examined microscopically by E. Zschimmer [11] on a set of plane polished plates of optical glass of different types which had been stored in a loosely closed metal box for periods up to seven years.

Dimming test.—Zschimmer [12] found that by exposing polished glass surfaces to moist air, nearly saturated with water vapor and heated to 80° C, for a period of two hours or longer, films form on the surfaces which are similar to the films formed at room temperatures on polished surfaces after months' or years' exposure to the atmosphere, Zschimmer's work was repeated and modified slightly by Elsden. Roberts, and Jones,[13] and accordant results were obtained by them. Constant temperature was maintained by means of a carefully regulated thermostat. Test plates, $1\frac{1}{2}$ by $\frac{7}{8}$ by $\frac{1}{8}$ inches in size with well

[9] Ber. d. deutsch. Chem. Ges. **22**, 1092, 1889; **24**, 1482, 1891; Zeitschr. f. Instrumentenkunde **9**, 117, 1889; **11**, 311, 1891.

[10] Ber. d. deutsch. Chem. Ges. **25**, 2494, 1892; **26**, 2915, 1893; **26**, 2998, 1893; Zeitschr. f. analyt. Chem. **33**, 299, 1893; **34**, 381, 1894.

[11] Chem. Zeitung, **25**, 730, 1901.

[12] Zeitschr. Elektrochemie **11**, 628–638, 1905; D. Mechan. Zeit., **7**, 53, 1903.

[13] Jour. Soc. Glass Technology, **3**, 52–69, 1920.

polished surfaces were first examined, after careful cleaning by a special method, for surface imperfections; these were recorded for each plate. Polished quartz plates served as control plates and were inserted into the apparatus together with the glass plates. In all, operations the greatest care was taken to insure clean glass surfaces free from contamination. The plates were then exposed in the apparatus to a slow current of moist air at 80° C. for the desired time. The thermostat was then cooled to a temperature of 2° C. below room temperature at such a rate that no distinct precipitation (dew) was formed on the quartz plates. The plates were then removed and quickly transferred to dry test tubes and the tubes closed with rubber stoppers. The plates were first examined for dew and a record was made in each case of the time required for the dew to disappear. The plates were then examined for "film" or degree of attack of polished surface; detailed examination under the microscope revealed the characteristic features of each deposit and from these an estimate was made of the degree of attack on plates held at 80° C. for 30 hours. On this basis the glasses were classified into three groups—excellent, medium, and poor.

Unaffected or very slightly affected	1
Appreciably affected	2
Seriously affected	3

The classification of the relative weather stability of different optical glasses by this method appears to be in accord with the actual relative behavior of the glasses toward weathering agencies, and also to agree with the conclusions reached by the iodoeosin test of Mylius.

The iodoeosin test.—Experiments by Warburg and Ihmori [14] proved that glass is attacked by water in such manner that some alkali is leached out; even in the presence of weak acids, it is the action of the water which is the important factor in the attack. The quantity of alkali thus set free on hydrolytic decomposition of the glass is indicative of the resistance of the glass to weathering agencies. The most sensitive and reliable method for ascertaining the amount of free alkali present appears to be the iodoeosin test of Mylius.[15]

For the iodoeosin test a saturated solution of water in ether is used in which pure iodoeosin ($C_{20}H_8I_4O_5$) is dissolved (0.5 g per liter solution). A freshly fractured surface of the glass to be tested is immersed for one minute at 18° C. in this solution; during this time the glass is attacked, a small quantity of alkali is set free, enters into combination with the iodoeosin to form the red alkali salt (soda or potash) which is insoluble in ether and hence is precipitated on the surface thus coloring it pale red, the intensity of the coloring

[14] Wiedemann's Ann., 27, 481, 1885.

[15] Zeitschr. Instrumentenkunde, 1905, 149; Zeitschr, Anorg. Chem., 55, 233–260, 1907; 67, 200–224, 1910; Silikat Zeitschr. I, 2, 25, 45, 1913. See also Hovestadt, Jena Glass, translation by J. D. and A. Everett, London, 1901; Zschimmer in Doelter's Handbuch d. Mineralchemie I, 855–918, 1912.

depending on the amount of free alkali available for precipitation. The glass surface, on removal from the iodoeosin solution, is plunged quickly into ether and the excess iodoeosin solution is washed off. The surface is then allowed to dry; the surfaces, except the freshly broken surface of the glass fragment, are wiped clean with a cloth; the iodoeosin salt is then dissolved in a small quantity of water and its quantity determined colorimetrically by matching it against a standard iodoeosin salt solution. The alkalinity of the freshly broken glass surface in terms of milligrams iodoeosin thus abosrbed per square meter area is called the "natural alkalinity" of the glass by Mylius. The "weather alkalinity" is, however, a better indicator of the weather stability of the glass and is in effect the amount of iodoeosin absorbed per square meter area on a freshly broken glass surface after it has been weathered by exposure to moist air for seven days at 18° C. and is then tested in the same manner as a freshly broken surface before such exposure. Mylius found that the "weather alkalinity" in the more resistant and weather stable glasses is not in general greatly different from the "natural alkalinity"; but that in the less stable glasses the "natural alkalinity" may be four times as great as the "weather alkalinity." Certain anomalies, especially in the borosilicates and the dense flint and barium glasses are less disturbing in the "weather alkalinity" experiments than in the "natural alkalinity" tests.

In the practical use of these tests certain precautions have to be observed which are emphasized by Mylius. Extended tests on glass of known degrees of weather stability have proved the general reliability of the dimming and the iodoeosin tests. In the case of the heavy flint and barium silicate glass the effects of the lead and barium on the iodoeosin may be disturbing if the prescribed procedure is not strictly followed; the presence of boron oxide in a glass may also cause trouble under certain conditions. The iodoeosin tests should be corroborated by other methods wherever possible.

Mylius divides glasses into five groups on the basis of the alkalinity of the weathered surfaces (weather alkalinity) as follows:

Class.	Type of glass.	"Weather alkalinity," milligrams per square meter.	Example.
I	Practically insoluble	0 to 5	Silica glass.
II	Resistance glass	5 to 10	Jena Geräte, pyrex.
III	Hard glass	10 to 20	Flints, best crowns.
IV	Soft glass	20 to 40	Ordinary crowns.
V	Poor glass	Over 40	

Optical glasses should have a surface alkalinity, after weathering, less than 40 milligrams per square meter.

The acetic acid test.—This test was first used by E. Zschimmer [16] and is especially adapted to show the spots which may develop on flint glasses as a result of finger marks (perspiration). A drop of an aqueous solution containing 0.5 per cent acetic acid and 0.05 per cent glycerine is allowed to remain for 24 hours on a polished glass surface. It is then washed off; the intensity of the resulting tarnish or coating is a measure of the tendency of the glass to develop spots as a result of finger marks. Modifications of this test have been developed, but they are of limited application and usefulness.

Autoclave tests.—Tests of the behavior of glass surfaces subjected to attack by water and acid solutions at high temperatures and pressures, such as water at 180° C., have been adopted at different plants to ascertain the weather stability of the glass, but the value of the procedure has been seriously questioned. During the war they were applied by Bichowsky [17] to a series of optical glasses and interesting results were obtained. The tests adopted were not quantitative, and the results obtained are subject to the personal judgment of the observer. Three types of solution were employed, namely, water, 5 per cent solution of sodium hydroxide, and 1:1 hydrochloric acid. Half-inch cubes of the glass were immersed in one of the solutions in a steel bomb and heated for 4 hours at 225° C. in the case of water, for 2 hours in the case of the sodium hydroxide solution. The hydrochloric acid tests were made in sealed combustion tubes held at 175° C. for 6 hours.

Bichowsky grades each glass cube according to its appearance after treatment in one of the above solutions as follows:

Grade.	Appearance wet.	Appearance dry.
9	Thick slushy film	Film more than 1.5 millimeter thick.
8	Thick film	Flakes off when dry.
7	Deep etching in stratches and corners	Thin film, flakes off.
6	....do	Thin film, does not flake off.
5	Opalescent film	Deeply etched.
4	....do	Not etched.
3	Film	Film.
2	Clear	Do.
1	....do	Clear.

His tests on different types of glass show marked differences in behavior in the different solutions. From the results he was able, however, to infer with some degree of assurance the general stability of the glass. Unfortunately his experiments could not be carried far enough on a sufficiently large number of glasses of known degrees of weather stability to demonstrate the practical usefulness of the method as a test for actual "weather stability."

[16] Deutsch. Mechaniker Zeit. 1903, 55.

[17] Journ. Am. Ceram. Soc., 3, 296–308, 1920.

THE FORMATION OF FILM ON INCLOSED GLASS SURFACES.

A serious matter during the war was the appearance in many optical instruments, especially binoculars, of a more or less pronounced film on lens and prism surfaces which reduced the light transmission seriously and in many cases rendered the instrument useless. In many instances it was found possible to clean the surfaces, but this necessitated in each case reassembly and readjustment of each instrument after cleaning. The "film" problem was attacked by many investigators and the source of trouble found to be in many cases lack of cleanliness in the original assembly of the instrument;[18] film of this nature is especially liable to occur on the graduated surfaces of reticules, of prisms, and of the field lens of the eyepiece. In certain cases the formation of film was traced back to lack of weather stability in the glass itself.

A faint film is recognized most readily in oblique, half-shadow illumination, rather than in direct full illumination. To detect film on a glass surface in an optical instrument, point its eye-piece end toward a strong light; turn the instrument through a small angle so that its axis does not coincide exactly with the line of sight from the observer to the source of light. Under these conditions of indirect lighting, film on a lens or prism surface appears as a faint haze, not unlike the effect produced by a ray of sunlight on suspended dust particles in a room. With proper care and an intense source of light, this test is extremely sensitive and renders visible even faint traces of film.

[18] H. S. Ryland, On the prevention of film in inclosed optical instruments, Trans. Opt. Soc. London, **19**, 179–181, 1918; L. C. Martin and C. H. Griffiths, Deposits on glass surfaces in instruments, Trans. Opt. Soc London, **20**, 135–155, 1918.

Chapter V.

THE MANUFACTURE OF LENSES AND PRISMS.

The operations and processes described in this chapter are for the most part different from those involved in the manufacture of optical glass; they are, moreover, more widely known and are essentially mechanical in nature, and hence do not require to any great extent the services of the chemist and the physicist. The maker of optical instruments on undertaking to manufacture an instrument to be used for a definite purpose ascertains first the exact optical and mechanical conditions, such as magnification, field of view, external dimensions, etc., which the finished instrument has to meet. The lens designer is then called upon to produce an optical system which will not only satisfy the optical requirements, but also fit properly into the given mechanical system. Guided by certain principles he computes the shapes, sizes, and positions of the several elements of a lens system which will best meet the prescribed conditions with the several types of glasses available; in the general design he relies not only on the results of computation, but also on the results of previous computations, and on his general experience with optical systems.

Having thus specified the shapes and sizes of the several optical elements of the system, it is the task of the manufacturer to fashion the desired lenses and prisms from the plates of glass received from the glass factory. The glass is treated throughout as a material on which certain operations have to be performed to attain certain results, just as brass or other metal which enters into the construction of an optical instrument is subjected to other operations to attain other desired results. Each material is characterized by certain properties which necessitate special modes of treatment in the factory in order to attain the desired results. It is the task of the optical engineer to prescribe the modes of treatment best adapted to produce these results with optical glass under given factory conditions. It is not the purpose of the present chapter to specify and to describe in detail the manufacturing processes best suited for the production of optical systems required in optical munitions; but rather to state in a general way the factory procedures and to emphasize certain fundamental principles, thereby directing attention to some of the difficulties which may arise in case a great increase in the production of optical munitions is demanded as a result of war-time conditions.

There is need at the present time for a comprehensive treatise on the manufacture of precision optics. The literature on the subject is scant and incomplete. The tendency in the optical trade is to keep secret all manufacturing processes and to overemphasize the difficulties encountered and the skill required to overcome them.

In the following articles certain phases of the general optical manufacturing problem are described:

Draper, H. On the construction of a silvered glass telescope 15½ inches in aperture, etc. Contributions to Knowledge, Smithsonian Institution, vol. 34, No. 1459, 1904.

Ritchey, G. W. On the modern reflecting telescope and the making and testing of optical mirrors. Contributions to Knowledge, Smithsonian Institution, vol. 34, 1904

Therelfall, R. On Laboratory Arts, London.

French, J. W. Trans. Opt. Soc. London, 17, 24–40, 1916; 18, 8–48, 1917.

Rayleigh, Lord. Proc. Optical Convention, 1905, pp. 73–79.

Halle, Bernhard. Handbuch d. praktischen Optik.

PREPARATION OF GLASS FOR LENSES AND PRISMS.

Before putting any raw optical glass into work it should be inspected for defects, such as striae, bubbles, stones, strain, etc.; otherwise unsatisfactory glass may be put into work only to be discarded later. During peace times, glass which is optically satisfactory and requires no further inspection can be bought in the open market, but in time of war the inspection is necessarily less rigid and poor glass may be passed by inexperienced inspectors. This glass, unless reinspected at the lens factory and rejected, is put into work and eventually causes waste of energy and time. This situation occurred time and again during the recent war, and in at least one instance retarded production seriously. A remedy for this situation is the accumulation, during peace times, by the Government of a sufficient quantity of raw optical glass of good quality to enable manufacturers to use it until new production of raw glass on a scale commensurate with the needs is well under way.

After the quality of the raw optical glass has been approved by the inspector, its preparation for lenses and prisms depends in part on the attitude of the manufacturer and on the sizes of the lens or prism elements to be made from it. It is possible from a given block of optical glass either to saw out lens and prism blanks or to press blanks of approximately the correct shape. Many manufacturers of optical instruments are not equipped with lens-pressing plants and are required either to have the pressing done elsewhere or to saw out blanks from the plates of raw glass. In some instances the lens-pressing process has been found to be more economical than the cutting process; but, in others, the cutting process is superior and cheaper.

THE SIZES OF PRESSED AND SAWED BLANKS.

In the grinding and polishing operations a certain amount of glass is necessarily wasted, and, in determining upon the sizes of the blanks to be used for the manufacture of lenses and prisms of definite shapes and sizes, the manufacturer makes proper allowance for this wastage. The amount of excess stock needed depends upon the size of the lens and the curvature of its surfaces. In case pressed blanks are to be used, several millimeters (3 to 8 millimeters or 0.1 to 0.3 inch) are added to each prism dimension to allow for irregular surfaces and for pressing or molding defects; the actual allowance increases with the size of the prism. In low-power lenses of large radii of curvature several (3 to 5) millimeters are added to the diameter to allow for centering of the lens; in higher power lenses of shorter radii of curvature an allowance of 2 millimeters to the diameter is sufficient; 1 millimeter extra thickness is allowed for grinding on each lens surface. Thus for a lens 20 millimeters in diameter the lens blank should measure 2 millimeters thicker and have a diameter 1.5 to 2 millimeters larger; for a lens 75 millimeters in diameter the blank should be 3 millimeters thicker and have a diameter 4 to 5 millimeters larger to allow for centering. In case the blanks are to be sawed from plates of glass an allowance of several millimeters should be allowed for each prism face. For a given hickness of glass plate the cutting of the platest should be so planned that a minimum of glass is wasted. The prisms may be so cut that the hypothenuse face is normal to, or parallel with, or includes an angle of 30° or 45° with the flat surface of the plate. The size and shape of the available plate of glass and that of the prisms to be cut from it are the determining factors in each case.

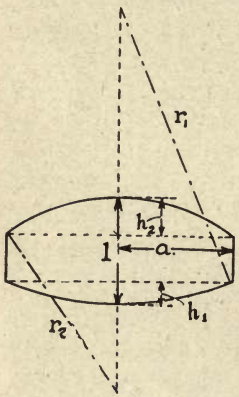


FIG. 74.—Diagram illustrating the several elements necessary to compute the volume of a lens. L is the thickness of the lens; a, the semidiameter; r_1 and r_2, the radii of curvature; h_1 and h_2, the height of the spherical segments.

In order to ascertain the weight of a lens or prism blank it is necessary to compute first its volume and then its weight from the known specific gravity of the glass from which the blank is to be made. In this connection the following formulae and tables are useful:

The volume, V, of a lens of semidiameter a, thickness l, radii of curvature r_1 and r_2, height of segments, h_1 and h_2 as indicated in figure 74 is

$$V=\frac{\pi}{3}[3a^2(l-h_1-h_2)\pm(3r_1-h_1)h_1^2\pm(3r_2-h_2)h_2^2]$$

in which the negative sign in the last two members applies to concave lens surfaces, the positive sign to convex lens surfaces. In this expression $a^2=h_1(2r_1-h_1)=h_2(2r_2-h_2)$.

A simpler approximate expression is:

$$V = \pi a^2 \left(l \mp \frac{a^2}{4r_1} \mp \frac{a^2}{4r_2} \right)$$

in which the negative sign is used for convex surfaces, the positive sign for concave surfaces. The values obtained with this expression are always too low; for $a/r = 0.243$, 0.341, 0.415, 0.477, 0.532, 0.723, respectively, the percentage errors are 1, 2, 3, 4, 5, and 10.

In the computations of the volumes and weights of lenses and prisms of different types of glass, Tables 15 and 16 are useful.

TABLE 15.

No.	Inches to centimeters.	Centimeters to inches.	Cubic centimeters to cubic inches.	Cubic inches to cubic centimeters.	Weight.	
					Cubic centimeters water in pounds.	Cubic inches water in pounds.
1	2.54	0.3937	0.061	16.39	0.00220	0.03613
2	5.08	0.7874	.122	32.77	.00441	.07225
3	7.62	1.1811	.183	49.16	.00661	.10838
4	10.16	1.5748	.244	65.55	.00882	.14451
5	12.70	1.9685	.305	81.94	.01102	.18064
6	15.24	2.3622	.366	98.32	.01323	.21676
7	17.78	2.7559	.427	114.71	.01543	.25289
8	20.32	3.1496	.488	131.10	.01764	.28902
9	22.86	3.5433	.549	147.48	.01984	.32514
10	25.40	3.9370	.610	163.87	.02205	.36127

In this table are listed the equivalents of centimeters (col. 2) to inches (col. 1); of inches (col. 3) to centimeters (col. 1); of cubic inches (col. 4) to cubic centimeters (col. 1); of cubic centimeters (col. 5) to cubic inches (col. 1); in columns 6 and 7 the weights in pounds of cubic centimeters and cubic inches of water, respectively (col. 1) are listed.

TABLE 16.

Specific gravity.	Weight of cubic centimeter of glass.		Weight of cubicinch of glass.	
	Grams.	Pounds.	Grams.	Pounds.
2.3	2.3	0.00507	37.960	0.08309
2.4	2.4	.00529	39.329	.08671
2.5	2.5	.00551	40.968	.09032
2.6	2.6	.00573	42.606	.09393
2.7	2.7	.00595	44.245	.09754
2.8	2.8	.00617	45.884	.10116
2.9	2.9	.00639	47.522	.10477
3.0	3.0	.00661	49.161	.10838
3.1	3.1	.00683	50.800	.11199
3.2	3.2	.00706	52.438	.11561
3.3	3.3	.00728	54.077	.11922
3.4	3.4	.00750	55 716	.12283
3.5	3.5	.00772	57.355	.12645
3.6	3.6	.00794	58.993	.13006
3.7	3.7	.00816	60.632	.13367
3.8	3.8	.00838	62.271	.13728
3.9	3.9	.00860	63.909	.14090
4.0	4.0	.00882	65.548	.14451

In this table are listed the weights in grams and in pounds of 1 cubic centimeter and of 1 cubic inch of glasses of different specific gravities (col. 1) ranging from 2.3 to 4. In the case of specific gravities given to the second or third decimal place the exact values can be ascertained by adding to the appropriate value of Table 16 the desired amounts read off from Table 15. Thus, the weight in pounds of a cubic inch of glass of specific gravity 3.62 is 0.13006 (col. 5, Table 16) plus 0.0007225 (col. 6, Table 15), or 0.13078. In this computation careful attention should be paid to the decimal points. As a general rule, it is simpler to state all dimensions in the metric system; on the majority of ordnance drawings, however, the dimensions are given in inches, and in this case the foregoing tables are useful. The following equivalents are also useful in these computations: One ounce equals 28.35 grams; 1 pound avoirdupois equals 453.4 grams; 1,000 grams equals 2.204622 pounds avoirdupois; 1 inch equals 2.540 centimeters; 1 centimeter equals 0.3937 inches.

The volumes of the several different types of prisms in common use are readily deduced and offer no difficulty to the computer.

The manufacturer having ascertained the volumes and weights of the several different blanks required for a particular instrument commonly adds a safety factor of 50 per cent to the total weights of optical glass required to cover losses from preparation of the glass for blanks, from pressing and other defects, from grinding and polishing, from breakage, and from rejections.

GRINDING AND MILLING OPERATIONS.

In case the raw glass plates available are of irregular thickness or are too thick, it is necessary to cut off thin plates or to grind or to mill the plates to the correct thickness. Of these processes grinding is commonly adopted and consists essentially in grinding down by hand one side of each plate with coarse emery or carborundum on a rapidly rotating, plane, cast-iron disk. A series of such plates, ground on one side and of about the same thickness, are mounted on a flat cast-iron plate or disk with blocking pitch (mixtures of pitch, pine tar, rosin, shellac, Venice turpentine, and beeswax in different proportions depending on time of year and size of blocking tool) and then ground with emery or carborundum flat against a horizontal, rotating, plane, cast-iron plate. During the first part of this operation the iron blocking tool is carefully watched and guided somewhat by hand in order to insure equal thickness of all plates. Thicknesses are measured by means of a caliper; the distance between the ground-glass surface and the surface of the iron blocking tool is measured at different points over the plate. The uniformly thick plates are then ground with finer abrasive; if necessary they are then remounted and the coarsely ground flat under-

surfaces of the plates reground with finer emery. For these grinding operations a large rotating, heavy iron disk 4 to 8 feet in diameter is generally used and serves the purpose well. In case the moistened abrasive does not remain satisfactorily on the rapidly rotating plate the addition of a little glycerine to the water is advantageous.

An alternative to the grinding process is to mill the plates with a diamond-charged milling tool on a milling machine. The milling tool is a solid or thick-walled, hollow cylinder of copper, or brass, or soft steel, 2 to 4 inches in diameter and 3 to 6 inches long. For coarse cutting, the tool is charged with diamond dust which passes through an 80-mesh but is retained on a 100-mesh seive. The copper cylinder is charged commonly by first cutting with a sharp engraving tool, mounted on a fixture attached to a lathe, a series of closely spaced longitudinal grooves or cuts which extend the entire length of the cylinder and include an angle of about 45° with the radius. These cuts resemble the chisel cuts on the copper disk saws described below and serve the same purpose. The grooves thus cut are filled with diamond dust mixed with thick oil; the cylinder is rotated slowly while a hardened steel roller is pressed against it, and the grooves are thus closed. The millers are recharged by the same method of grooving and filling. Brass and soft-steel cylinders are harder and are commonly charged by direct pressure, the diamond dust of the dust-oil mixture being forced into the metal by the action of a narrow hardened steel roller bearing heavily against the slowly rotating cylinder.

The diamond-charged milling tools are mounted in a milling machine and the glass plates are carried forward on a moving bed as in ordinary milling operations. Kerosene or some soap compound serves as lubricant. The tools are run at high speed from 500 to several thousand revolutions per minute and care is taken not to take too deep or too fast a cut otherwise the tool may chatter and in certain instances shatter the plate.

Glass plates having irregular flat surfaces can be rapidly cut down to proper thickness with plane parallel sides by a miller of this type which is in common use in many optical grinding plants at the present time. It is possible by means of two heavy brass plates one-fourth inch thick mounted on an arbor and charged with diamond dust both on the end and down the sides to make a straddle mill for cutting blocks with parallel sides. In this case care should be taken to mount the glass blocks securely.

THE CUTTING OF GLASS.

From a thick plate of glass slices or strips of glass of given thickness are commonly cut by means of saws, specially designed for the purpose. A great variety of such saws are in use; they are commonly

disks of thin metal, such as copper, brass, tinned or untinned soft sheet iron or steel, impregnated with fine diamond dust. The speed and lubrication of the saw depend somewhat on the way in which the diamond dust is embedded in it.

In one type of diamond saw fine diamond dust (80 to 100 mesh) mixed with thick oil is introduced along the periphery of the saw by filling it into fine crosscuts made with a sharp chisel edge and then closing the cuts by means of an accurately fitting hard-steel roller pressed against the edge of the slowly rotating disk. The cuts are made commonly by hand and in direction are intermediate between radial and tangential cuts. During the cutting operation the disk, which is generally of copper and of stock one-sixteenth inch thick for saws up to 5 or 6 inches in diameter, and correspondingly heavier for larger saws, is held firmly between two plates on an arbor in the lathe, the rim of the copper disk extending one-eighth to one-fourth inch beyond the plates. With this method of mounting the plate retains its shape during the charging process. The edge is commonly rounded slightly and the transverse cuts are made as close together as possible. In operation the saw is rotated against the cuts. A saw of this type, properly used and well lubricated, should last for many days. Kerosene or some soap compound is used as cooling lubricant and, if high speed be used, is squirted under pressure in a steady stream against the saw cut in the glass which is thus kept cool and does not become overheated. Speeds of 1,000 revolutions per minute and even greater with small saws are satisfactory. Saws of this type cut readily through glass plates at the rate of one-half inch or more per minute; as the saw wears down it should be fed more slowly. Too much pressure on the saw cuts out the diamond dust and causes trouble. The saw should always bear against a flat surface and not against a sharp edge of glass; otherwise it is liable to be bent or damaged.

A variation of this type is made of brass disks one-sixteenth inch thick for 4-inch saws and three-thirty-seconds inch thick for 6 or 7 inch saws. Except for an outer ring one-eighth inch wide, the thickness of the metal disk is reduced slightly by cutting on a lathe in order to afford clearance and thus to reduce friction in the rapidly rotating disk during the glass-cutting operation. Even when no effort is made to insure a thicker rim, the filling with diamond dust by the ordinary process accomplishes the purpose to an appreciable degree. The edge itself is flat and is charged with diamond dust (80 to 100 mesh), mixed with heavy oil, by means of a hardened steel roller pressed against the edge while the disk mounted between circular plates is slowly rotated in the lathe. The disk is then mounted against a flat plate on an arbor and the powder is pressed into its rim on each side of the plate by means of the steel roller.

Small disks of this type in operation may be rotated at from 2,000 to 3,000 revolutions per minute and are lubricated along the cutting edge by a stream of kerosene under pressure.

Diamond-charged saws of the above types may be mounted in series on an arbor of a milling machine and a multiple gang saw thus obtained which cuts from a glass plate a series of strips of definite thickness. These strips may then be mounted in a supporting frame and cut crosswise into small square plates suitable for the manufacture of lenses after the corners have been chipped and ground off to obtain disks of the desired diameter.

In other saws a thick mixture of coarse carborundum powder and water is fed against the cutting edge of the rotating metal disk (commonly of sheet iron) and the glass plate is thereby cut with fair speed. The abrasive may be fed to the disk by having it dip into the thick carborundum-water mixture contained in a pan below the wheel.

Thin carborundum wheels running at a fairly high rate of speed have also been successfully employed for cutting glass plates.

In all cases the speed of the cutting saw and the rate of feed of the cooling lubricant should be so adjusted that a rapid and satisfactory cut is obtained without crowding the saw too severely and without chipping the glass seriously. The glass plate should be securely mounted on a support relatively free from vibrations.

In the case of thin plates of glass the crosscut sawing operations are generally dispensed with and the cuts made either with a glazier's diamond or a steel-wheel glass cutter.

EDGING OF DISKS.

Square plates of the desired thickness are made into disks by cutting and nipping or grinding off the corners. The usual practice is first to cement a number of such plates, cut and nipped to approximately circular shape, with paraffin into a column; an alternative is to use the plates dry or with a thin film of moisture on each surface and to hold them in place by a spring against the end of the column; to mount the column on a rotating axis and to have this play first against a carborundum grinding wheel which removes all corners and produces finally a column of uniform diameter. For the fine grinding operations either a fine grinding wheel or a diamond-charged miller is used.

An alternative method for the production of glass disks is to cut them directly from the glass plate on a drill press. For this purpose a hollow cylinder of brass or soft steel of the proper diameter and 2 millimeters thick is used. Several longitudinal grooves 4 or 5 centimeters long and 2 to 3 millimeters wide are cut into the sides

of the cylinder; along these grooves the thick mixture of carborundum powder (150 mesh) and water is fed to the cutting edge, which may be a smooth or a serrated edge. The glass plate is mounted securely to the bed of the drill press; the cylinder grinding tool is attached to the axis of the drill press and is rotated at about 500 revolutions per minute. The glass disk is cut out as in an ordinary drilling operation, the rate of cutting being about 1 millimeter per minute. The diameter of the cutting tool should be slightly larger (1 to 2 millimeters) than that desired for the glass disk. In operation a relatively large amount of the thick abrasive paste is used and is continuously worked over by hand and forced down the feed grooves of the rotating tool. Cylindrical tools in which the cutting end and rim are charged with diamond dust may be used in place of the carborundum; but in this case care should be taken to have longitudinal grooves both inside and out as well as indentations along the cutting end to provide for adequate circulation of the kerosene or soap-compound lubricant.

A more primitive method for edging glass disks preparatory to lens grinding is to cut the glass plate into squares with a glazier's diamond point, to cut and chip off the corners of each square with a pair of pliers, to cement it then with sealing wax or shellac on one end of a rod of metal or wood, to mount the rod in a lathe; and then with a mounted diamond point or a sharp three-cornered tool, made by grinding smooth the surfaces of a three-cornered file, to chip off carefully the protruding corners of the disk rotating with a surface speed of not over 10 feet per minute and thus gradually to work it down to a smooth circular edge. During this operation the glass edge should be kept moistened with kerosene or turpentine. A grinding-wheel attachment can also be used and with it the edge can be ground down to a circle of the proper diameter.

Prisms are commonly sawed from glass plates. The particular plan to be followed in order to waste as little glass as possible is determined in each case by the dimensions of the glass plate and by the shape and size of the prisms to be cut from it. The use of the milling machine for precision work in grinding prism surfaces will be considered in a later section.

THE PRESSING OF LENSES AND PRISMS.

In many optical shops the raw glass is molded first into the approximate lens or prism shape and size before it is given to the grinders and polishers. The pressing into blanks thus avoids the cutting and grinding operations described above, and were it not for certain defects which are thereby introduced, such as folds, feathers, and other pressing defects, and poor annealing, there is no doubt that the pressing method would be used to the exclusion of all others.

Special furnaces and presses are required, but the great saving both of glass and of grinding operations more than offsets the initial expense.

Raw-inspected optical glass which is to be pressed into lens or prism blanks of a special size is first cut or broken into fragments of the required weight. For this purpose steel trimming blocks (fig. 52, p. 172) are used with weighted, soft fiber or celluloid hammers; the sharp edge of the steel trimming block serves as contact point for the glass plate; a sharp blow with the celluloid hammer on the upper side of the glass plate at a point between the edge of the steel block and the hand supporting the plate suffices to fracture the glass plate at the desired point. The glass is first cut with a glazier's point into sections of about the correct weight. Each section or fragment is

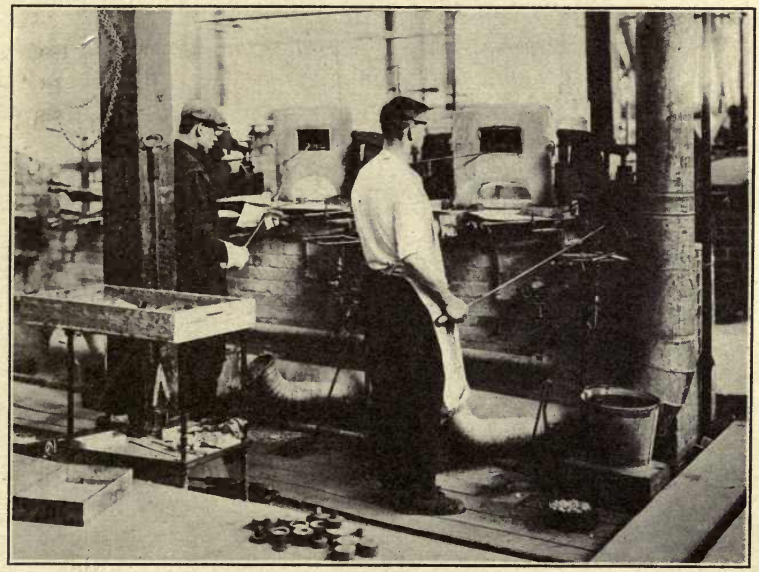


FIG. 75.—The pressing of small lenses and prisms. (Photograph by J. Harper Snapp at plant of Bausch & Lomb Optical Co.)

then trimmed to the exact weight, as determined on a small beam balance, on the one pan of which either a pressed blank or its equivalent weight is placed. In the trimming operations all sharp angles, especially reentrant angles and bruised or cracked portions of the glass fragment are trimmed off, in order to avoid folds during the melting down of the glass. The finished glass fragments are placed in a properly labeled tray in which they are transferred to the pressing department.

Large pieces of glass for large lenses or prisms are placed in a preheating kiln and gradually heated over night to a dull red heat; smaller pieces, intended for eyepiece and other small lenses are preheated directly in the pressing muffle furnaces. The muffle furnaces

are heated from each side (fig. 75) by a compressed-air gas jet which plays against the refractory arch crown of the heating chamber; the glass fragments to be melted down are placed on a base-plate of refractory material and are heated chiefly by radiation from the crown of the furnace. The operator stands in front of the furnace, which is built at a height convenient for ease of operation, and watches the progress of melting of the glass fragments. In order to prevent these from sticking to the refractory base-plate a thin layer of fine powder (clay, alumina, mica, talc, graphite, or a mixture of these) is spread over the plate; this powder adheres to the molten glass and, like flour on sticky dough, effectively coats its outer surface. The disadvantage of using powder for this purpose lies in the fact that the operator in shaping the irregular glass fragment as it gradually softens is liable, by too much working of the glass, to infold some of the dust-laden surfaces; so that they appear in the finished lens or prism blanks as pressing defects. With careful operators the rejections of pressed blanks because of pressing defects are not high; but a careless or inexperienced operator may spoil a large number of blanks in a short time if left to himself.

In the muffle furnace the glass is allowed to become reasonably soft. In the majority of muffles the heating is from the top down; but in others the base-plate itself is heated in addition. This results in a more uniform melting of the glass fragment. In all cases, however, the top surface softens first and flows down and tends to spread out over the base-plate. The operator prevents it from doing this by the use of flat iron paddles or rods with flat ends (fig. 75); with these the glass mass is molded approximately to the shape of the mold in which it is to be pressed. In the case of lens blanks he endeavors to produce a round disk of a diameter somewhat greater than that of the finished blank; in the case of prism blanks he shapes the soft glass into approximately the desired prism shape.

The softened glass, properly shaped, is slid along the base-plate to the cast-iron mold and is transferred in it to a plunger operated either by foot power or by compressed air or by hydraulic pressure. Presses for small lenses are commonly pneumatic presses; for larger work hydraulic presses are preferred. The iron mold, in which the softened glass is shaped, is preheated by means of gas burners in order that the glass be not too rapidly chilled. In all pressing operations it is essential that the rate of cooling be not too rapid, otherwise fine surface crackling results which can not later be removed.

The pressing molds are commonly made of cast iron and serve the purpose well. (Fig. 76.) The chief difficulty encountered with their use is the tendency of the glass blank to stick in the mold; it is then removed by tapping the mold. In the case of small molds it has been found advantageous to make them of tool steel and to place

in the bottom a closely fitting plunger to which is attached a short pin that extends through the bottom of the mold. These molds can be made more accurately and with better finish than cast-iron molds. The blank after pressing in this kind of mold is removed by tapping the extension pin of the plunger against the furnace plate; this raises the plunger and the glass blank is thereby loosened and drops out.

The pressing furnaces are made of different sizes depending on the size of blanks to be pressed. In the small muffles provision is made by the addition of an upper compartment to keep the sheet-iron tray or box of small blanks hot until the tray is full and ready to be transferred to the annealing furnace. Provision is also made in most furnaces to shield the operator from the furnace heat. There are different ways of doing this; in one, a series of chains is hung in front of the furnace, but they are interrupted at one point by a sheet of heat-resistant glass through which the operator sees his work; an

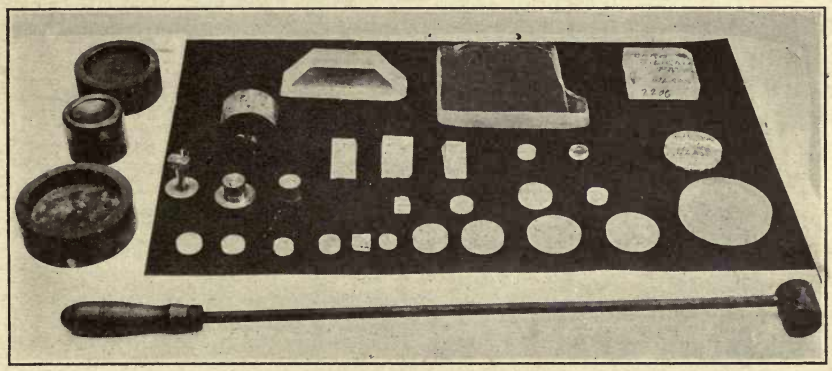


FIG. 76.—Molded prism and lens blanks; and the molds for pressing them. Frankford Arsenal.)

upward flowing, forced current of air conducts the heat away from the chains; in a second type a stream of fresh air is blown against the operator, and passes between him and the furnace; in a third a water curtain is employed.

In actual pressing operations a number of fragments are kept in work, so that there is always one fragment practically ready for the press. The output varies with the size of the blank. Thus an average output per press per working day is 2,000 or more eyepiece lens blanks or spectacle lens blanks; 800 or more binocular prism blanks, 150 large reflecting prism blanks 2 to 3 inches on a side. Greater skill is also required to produce the larger prism and lens blanks.

The method proposed by Capt. H. C. Fry, jr., to avoid the appearance of dusty surfaces and consequent folds and laps in pressed blanks, by heating the glass fragments on the end of a punty in a glory hole and paddling the softened glass gradually into shape with

flat copper or iron tools, has been tried out in a small way by the Bureau of Standards. The method produces clear, clean blanks, but it is slow and obviously best adapted for large blanks and less suitable for small lens and prism blanks. It may, however, be possible to develop a production method based on this principle which will meet the factory needs better than those at present in use.

In the pressing of large blanks the operator has constantly to guard against a too rapid heating of the outer surface and consequent flowing down and spreading out of the glass, otherwise folds are certain to appear. During the actual pressing operation, the speed of the plunger, which is kept hot by means of a gas flame, should be so regulated that the glass is properly pressed without the appearance of heavy surface crinkles or of fine surface cracks in the pressed blank. The pressing operation is in all cases a violent procedure. The soft glass when placed beneath the press has the consistency of thick pitch; the plunger descends and, in a period of time generally less than a second, the irregular mass of glass is forced to flow and to fill the mold. The soft glass tends to flow under these conditions somewhat as a lava flow, namely, in waves; with the result that in many instances the powdered surfaces are infolded and spread out in the direction of flow. A "feather" results, and the blank is rejected.

It appears that careful study of the factors involved in the pressing operations should enable the factory engineer to prescribe a better routine practice than the present method and thus avoid a certain percentage of the rejections which occur in pressed blanks.

The procedure for the annealing of pressed blanks is described in detail in Chapter III and need not be repeated here. Suffice it to state that in the annealing of large blanks careful attention should be given to the attainment of uniform temperature at the prescribed annealing temperature and also to the rate of cooling in order that appreciable strain be not then introduced.

THE GRINDING AND POLISHING OF PRISMS.

Prisms intended for use in optical instruments are glass bodies of geometrical shape and bounded by flat surfaces. In precision optics the prisms must be of definite dimensions; their surfaces must be optically flat and the interfacial angles must be correct within a few seconds of arc in certain instances. These conditions are difficult to meet and nice attention to details is essential to produce the desired results.

The first operation in the grinding of prisms, whether in cut or in pressed blanks, is to grind flat one of the surfaces which in the finished prism is a side or end surface and is left as a frosted, unpolished surface; in a right-angled prism, for example, these surfaces are the

triangular side surfaces. This ground surface serves as a surface of reference for future operations. The rough grinding is commonly done by hand on a large rotating, horizontal iron disk, 3 to 5 feet in diameter, and rotating fairly rapidly. Coarse emery, or carborundum, or crushed steel either 90 or 150 mesh is used.

The prism surfaces at right angles to the first base surface are now roughed out in similar manner; the angles between the surfaces are checked by means of accurate angle gauges.

A number of rough-ground prisms (20 or more) are mounted with the ground faces in contact with a heated flat iron disk; a thin layer of beeswax, paraffin, or rosin and beeswax serves as cement. (Fig. 77.) The disk is allowed to cool down and the second side surfaces of all

FIG. 77.—The blocking of prisms for rough grinding. Angle plates into which partially finished prisms are fitted for the grinding of additional faces. Prisms cemented to a flat plate preparatory to grinding are also shown. (Frankford Arsenal.)

prisms are then ground down together, the tool being either held or guided by hand so that the newly ground surfaces are parallel with the first surfaces. (Fig. 78.) These surfaces are first ground with coarse emery or carborundum of 90 mesh; then successively with 150 mesh, 220 mesh, and smoothing abrasive. In each case the change from a coarser to a fine abrasive is made when examination of the ground surface shows it to be free from scratches and of uniform granularity; the edges should be free from chips. The coarse grinding is done on a large horizontal iron disk; but for the fine grinding flat iron disks about 18 inches in diameter and rotating at about half the speed of the large roughing plates are used. The smooth grinding of the second side surfaces having been finished, the prisms

are remounted and the first side surfaces are reground until the prism has the prescribed thickness as measured by a gauge or caliper directly on the mounted prisms. In all grinding operations it is essential that care be taken not to mix the grades of abrasive; for this reason the operators work with uprolled sleeves, and commonly use only one group of abrasives, either the coarse or the fine; thus the rough grinders operate only on the large roughing disks. The plates are scrupulously cleaned before passing to a finer powder, in order that no single coarser grain be left to produce scratches.

After the two side surfaces have been ground and smoothed so that all prisms are of uniform thickness, the prisms are thoroughly cleaned and are then cemented with beeswax or paraffin, side by

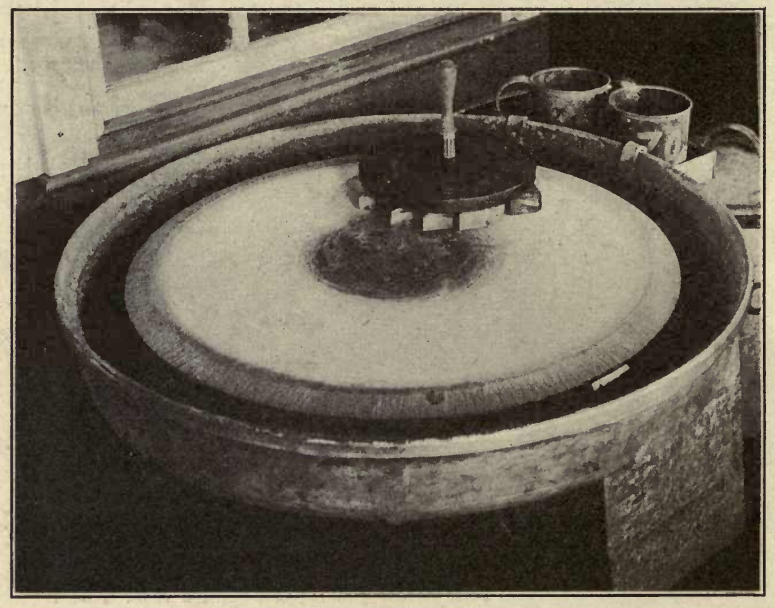


FIG. 78.—The rough grinding of a block of prisms. (Frankford Arsenal.)

side, in a special angle tool; the large surface, such as the hypothenuse surface of a right-angle prism, is ground first, the sides of the prism having been fitted into the right-angle grooves of the tool. The exposed surfaces are ground with the several grades of emery and finally smoothed, care being taken to grind down all sides of the block uniformly. The side surfaces likewise are mounted in special angle tools and ground as above. Each prism is now bounded by flat surfaces; the side surfaces are perpendicular to the other surfaces; the angles between the remaining surfaces are also approximately correct.

The prisms are now ready for blocking and polishing. An optically flat, thick iron disk between 8 and 16 inches in diameter is heated until

paraffin melts on it. Small flat pieces of glass are first placed around the edge of the tool, then the prisms are grouped over the tool, the face in each prism to be polished being placed down on the tool in the paraffin. The smallest face is commonly the first to be blocked; thus in a right-angled prism the side surfaces are polished before the larger hypothenuse face. The prisms are pressed firmly against the tool and allowed to cool; the exposed surfaces are then painted with a thin layer of beeswax.

A brass ring or band is now clamped around the tool; its height should exceed that of the largest prism on the block. (Fig. 79.)

FIG. 79.—Prisms in process of blocking with plaster of paris for polishing. On the right there is a block of prisms ready for polishing. (Frankford Arsenal.)

The basin thus formed is nearly filled with a mixture of water and plaster of Paris. For some purposes the plaster of Paris is mixed with a little Portland cement in the proportion 10 to 1. A flat iron disk is placed, with four or more holes drilled through it, on top of the cement; the holes are filled with the plaster mixture. The cemented block is allowed to set and harden for about 16 hours. The hardening process can be expedited by placing the blocks in a drying cabinet together with phosphor pentoxide or calcium chloride.

After the cement has set, the iron plate is heated to the melting temperature of the paraffin and the plaster block is slid off the iron plate. The prism surfaces to be polished are now exposed.

The plaster is cut away to a depth of one-eighth inch from the prisms so that they alone touch the grinding and polishing tools.

The optically flat, thick iron blocking tool is cleaned and heated to the temperature of melting beeswax. The plaster block with the carefully cleaned prisms is placed face down on the heated iron disk; in certain instances it is advisable to bear heavily down with a screw press or with added weights on the plaster block in order to insure strict parallelism of all exposed prism surfaces, after the block has cooled. The cold block is removed from the tool; the plaster is coated with two coats of shellac in order to shield it from water during the grinding and polishing operations. After the shellac has become thoroughly dry the block is ready for fine grinding. (Fig. 79.) For this purpose a slightly convex grinding plate is used rather than a perfectly flat plate, so that the surfaces after fine grinding will be slightly concave. Experience has shown that it is easier to polish from slightly concave to plano or from the margin to the center than vice versa. The grinding plate may well be smaller than the prism block. The amount of depression between center and margin in a prism surface after fine grinding should be less than 0.001 inch.

Flour emery for finishing is obtained by washing emery, which has been used in previous operations, in clean water and allowing it to settle out. The longer the time required for the settling, the finer the emery deposited. For the final finishing, emery that remained in suspension for 10 minutes but had been deposited at the end of 60 minutes is commonly used. Different methods are in use at different factories for the grading of emery and of carborundum, all of which depend on the rate of settling of different sized particles of the abrasive in clear water. Difficulties are encountered because of the tendency of thin flakes to float, to remain in suspension, or to adhere to the sides of the settling tanks. It is a good plan to reclassify each fractional settling to insure, so far as possible, the elimination of larger particles which might cause much damage. In the case of carborundum the grading is especially difficult, but with care it can be satisfactorily accomplished.[1]

The fine grinding-tool is rotated relatively slowly; the fine emery and water are rubbed over it, the prism block is placed upon it and is rubbed and rotated evenly over the plate so that all sides of the block are equally ground. Care should be taken to keep the emery wet, because, if too dry, it tends to form spherical aggregates or balls which then scratch the surfaces badly. After grinding for five minutes the prism surfaces should be cleaned and inspected with a magnifying glass. If they appear free from scratches and pits and the surfaces have a uniform velvet finish, they are ready for polishing,

[1] W French Trans. Opt. Soc. London, 19, 1918.

after they have been thoroughly cleaned with a brush and every particle of abrasive has been removed from the prism block.

The polishing tool is prepared by melting clean strained Norwegian pitch to which a little rosin has been added and pouring the viscous liquid on a flat horizontal iron tool to a depth of one-fourth inch. Strips of wet paper placed around the edge of the tool prevent the pitch from overflowing. In cold weather add a little pine tar to the pitch in order to soften it slightly. After the layer of pitch has become cold two series of parallel grooves, mutually perpendicular, about one-eighth inch wide and 1 inch apart, are cut into the pitch

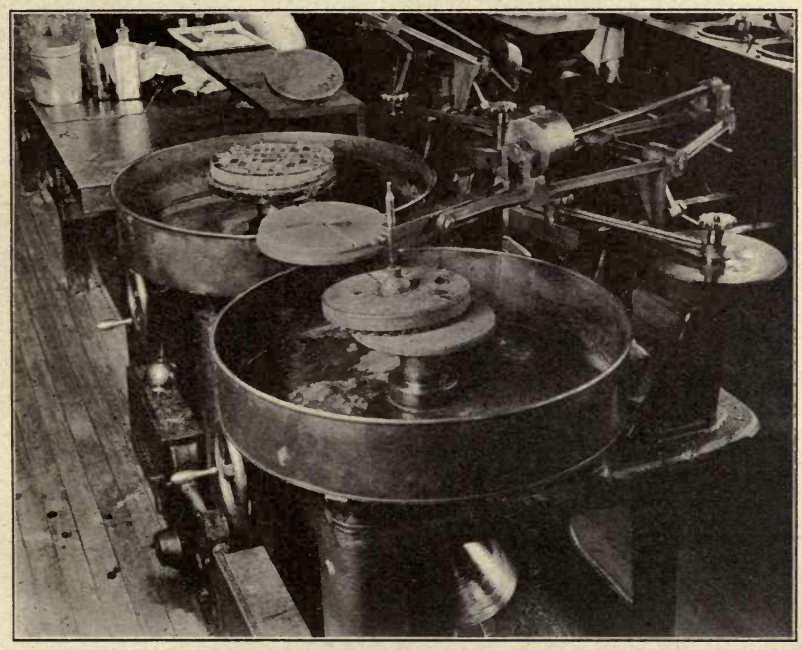


FIG. 80.—Polishing a block of prisms and a block of lenses of large radius. (Frankford Arsenal.)

surface. The pitch is then reheated sufficiently to soften its upper surface upon which then a cold, flat, or slightly concave iron tool is pressed, which is moistened with a creamy mixture of water and rouge or dilute glycerin to prevent its sticking to the pitch. This imparts to the pitch surface the exact negative of the surface of the iron tool. The iron plate may be pressed against the pitch surface directly after the first heating if desired, and the grooves cut in afterwards. (Fig. 80.)

Instead of an iron blocking tool Ritchey [2] uses blocks consisting of nicely dovetailed oak pieces, made in layers and impregnated with paraffin to prevent warping. These blocks change their shape to a

[2] Contributions to Knowledge, Smithsonian Institution, 34, No. 1459, 1904.

less degree with change in temperature than do the iron blocks and for certain kinds of work are preferable.

With a slightly convex polisher the tendency to polish a convex surface because of the greater action near the periphery of the polisher is counteracted. A similar effect can also be attained by increasing the width of the grooves toward the margin of the polisher. In the polishing operation a small quantity of a thick, creamy mixture of rouge and water is spread over surfaces of the prisms in the blocks mounted on a polishing machine so that its axis of rotation is vertical. Upon it is placed the polisher which is attached above by a pin in a socket at the center of the polishing disk to an arm which moves it back and forth across the rotating plaster block. The polisher is free to rotate and does so in the same direction as that of the rotating plaster block. When short strokes of the polisher are used the greatest wear is at the center of the plaster block and the prism surfaces tend thereby to become concave; when long strokes are employed so that the polisher extends well over the edge of the prism block the greatest wear is along the periphery of both polisher and block, and the prism surfaces tend then to become convex.

The polishing process is necessarily slow. Precision polishing requires slow movements and well-lubricated surfaces to prevent the heating up of glass surfaces. If the polisher runs hot, as is the case with spectacle lenses, the exact figure is lost and only low precision work can be obtained. In all precision optical work patience is essential.

The polishing tool is commonly of slightly smaller diameter than that of the block of prisms. A circular stroke of the polisher is generally employed but a straight chordal stroke may be used with success when certain precautions are taken. Corrections for slight curvature of surface are usually made by lengthening the stroke of the polisher in case the surface is slightly concave, and decreasing the stroke in case the prism surfaces are slightly convex. It is possible, however, to use the same length of stroke and to correct for curvature by changing the curvature of the pitch surface of the polisher.

The time required to polish a block of prism surfaces depends somewhat on the size of the block and on other details; commonly four to eight hours suffice. The prism surfaces should be inspected with a magnifier for quality of surface polish, especially for freedom from scratches, small pits, and grayness of surface; and for flatness of surface by means of an optically flat test plate. When a test plate is placed above a prism surface and moved so that it is practically parallel with the prism surface the Newton interference colors of thin air films appear. (Fig. 81.) If the interference bands are perfectly

straight to the extreme edge and, when the surfaces are in a more nearly parallel position, only one interference color is seen to extend over the entire plate, the surface is sufficiently flat. The use of a monochromatic light source, such as the sodium flame or the green mercury lamp when viewed through a mercury green filter, facilitates the observation of interference fringes.

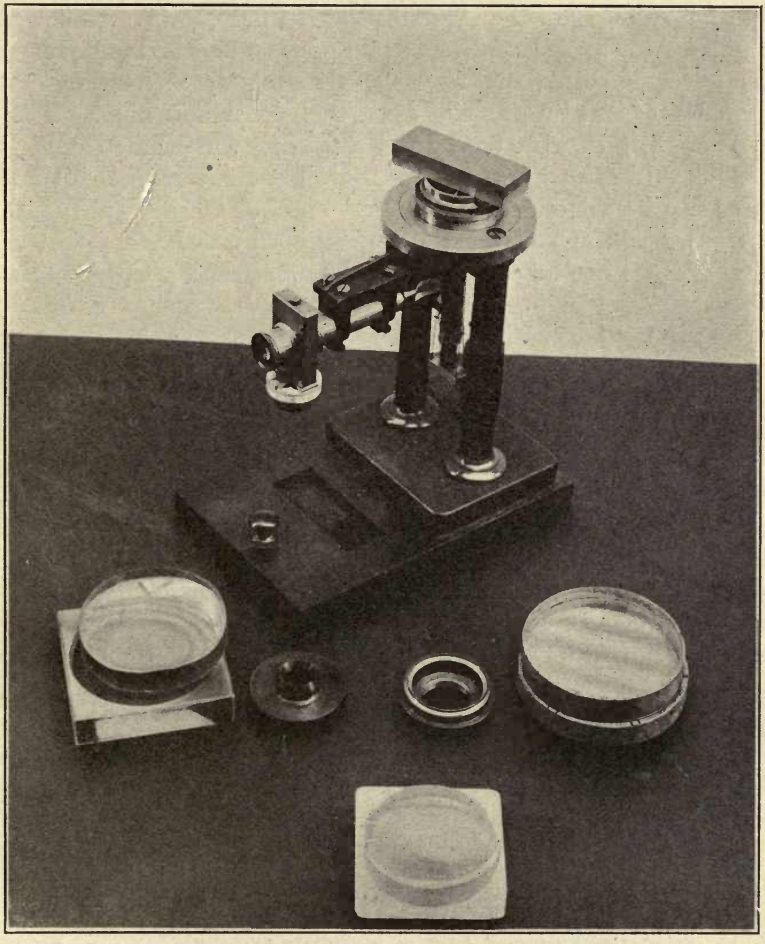


FIG. 81.—Spherometer and test-plates for measuring radii of curvature of lenses. The test plates show the Newton color fringes. (Frankford Arsenal.)

Toward the end of the polishing process the polisher is run nearly dry in order to give a perfectly grainless polish.

The prisms are removed from the plaster block by first breaking the block itself away from the iron plate with a chisel, and then by tapping the plaster block with a hammer lightly; it breaks apart easily and the prisms are readily separated from it and are then

cleaned with benzene or gasoline to dissolve off the beeswax or paraffin.

The next operation is to test and, if necessary, to correct the angle between the polished face and an adjacent finely ground but unpolished face. One arm of an angle gauge with the required angle is placed against the unpolished face and slid down it until the second arm comes into contact with the polished face. If the prism angle is greater or less than the prescribed angle, light can be seen between the gauge arm at the near or far side of the polished surface. The angle is corrected then by hand by grinding with smoothing emery on a flat tool and by pressing upon the end that is high. It is not possible to correct prism angles satisfactorily by polishing alone. The correction of angles by handwork must be carefully done, otherwise errors may be introduced which can not be remedied by polishing alone. As soon as the prism angle has been satisfactorily corrected the prism face is ready to be polished by the process outlined above. The reason for starting the polishing with the smallest face is now obvious; it is the most difficult face to grind as a flat surface by hand, and its correction by hand for angle is therefore less favorable than that of the larger surfaces.

The foregoing operations are carried out for all faces of the prism. In the practical operations experience is required to know exactly when to stop one operation and to begin another, as, for example, when to change from one size abrasive to the next finer grade; also to know the optimum speeds at which to grind or polish with different sizes of blocks and with different types of glass.

In many instances better results are obtained by polishing the prism in mounted blocks rather than individually. Thus in the case of the Dove reflecting prism, which serves as the vertical rotating prism of the panoramic sight, the end surfaces are relatively small; the prism is in fact the truncated base of a large right-angled reflecting prism. Better results are here attained by cementing strips of plane-parallel plates of glass to a series of these prisms and thus by completing the right angle to produce a much larger bearing surface and correspondingly greater accuracy. In case it is not desired to heat up the prisms in the cementing operation, sodium silicate may be, and has been used successfully as a cement; the glass strip cemented with sodium silicate is removed finally by grinding.

Roof-edge prisms, such as the elbow prism in the panoramic sight, are best polished in pairs. The final corrections for angle are commonly made by hand on one surface only; a high degree of skill is required to produce this type of prism.

The chief difficulty encountered in the production of optical flat surfaces is not the grinding and polishing of these surfaces to the desired precision in the mounted block, but the fact that on removing

the prisms from the block certain strains are released, and these cause the optical surfaces to warp and to lose to some extent their optical quality. The release of strain is, moreover, not instantaneous, but takes place gradually, so that the surfaces may continue to change slightly for an appreciable period of time. The cement with which the glass is cemented has a coefficient of expansion different from that of the glass and on cooling strains the glass unequally. Efforts have been made successfully to overcome this difficulty by cementing the flat surfaces to the flat tool, preferably of glass in this case, by optical contact or by capillary attraction using for the purpose a thin film of liquid.

The plates may also be weighted with pieces of lead and then cement (rosin and oil) placed around each plate. To enter further into the details of these methods, which are especially useful in the preparation of sextant mirrors, would lead too far in the present general description. Suffice it to state, it is possible by giving proper attention to manipulation to cement many surfaces by optical contact and thus to avoid the troubles arising from the use of ordinary cements. It is common practice, for example, to cement by optical contact the surfaces of two roof-edge prisms which are to be polished in pairs. Surfaces to be placed in optical contact must be chemically clean. A very slight warming of an optically flat surface of a plate or prism causes it to warp and become slightly convex momentarily; a warm prism or plate placed against the optically flat surface of a tool causes the tool surface to expand, and hence to become convex upward. Under these conditions optical contact between the two surfaces is first established at the centers, and on slight cooling readily excludes the thin film of air which under ordinary conditions is liable to be entrapped and thus spoil the optical contact over the entire area. The placing of optically flat glass surfaces into optical contact is, however, an art which can be acquired only by practice. Pressure clamps are applied in certain cases to force the two flat surfaces gradually into optical contact.

The strains and movements which result on embedding the prisms in a large mass of plaster of Paris have been reduced to a certain extent by using specially constructed iron gratings or ribs. These divide the entire block into a series of small compartments each one of which is filled with the plaster of Paris; the iron walls reduce the range of action of strains which may be set up on the setting of the plaster.

PRECISION MILLING OF PRISMS.

During the war an ingenious method for the milling of precision prisms was developed by Capt. W. R. Ham, of the Ordnance Department, and was successfully used for the production of the elbow, vertical-rotating, and rotating head prisms of the panoramic sight.

For the purpose a precision milling machine is essential. Diamond charged cylinders of brass and of soft steel are used for the milling operations. The brass cylinders are charged with coarse diamond powder (80 to 100 mesh), the soft-steel cylinders are charged with the fine diamond dust which has remained in suspension in water for five minutes. In each case the diamond dust is rolled in by means of a narrow, hardened, steel roller. The charged cylinders, about 2 inches in diameter and 3 inches long, are then rolled between three hardened steel rollers, accurately mounted and exerting heavy pressure on the charged cylinder, which is thus straightened and rendered of uniform diameter. This is essential for precision work.

The glass which is to be ground to prism shape is then mounted in a fixture. Accurate settings for position are made commonly by reference to a finished prism of acceptable quality and mounted on the same axis with the prism to be ground. An autocollimating telescope of high resolving power is sighted on a finished prism and determines the amount of rotation necessary to pass from one prism face to a second. The coarse brass cylinder mill is first used, then the fine soft-steel mill for the finishing cuts on each face. The faces thus prepared are remarkably accurate in position and are ready without further preparation for blocking, which if properly done practically insures satisfactory interfacial angles between the finished prism faces. The application of this method means a considerable saving of time and energy in the making of difficult prisms, such as the roof-edge reflecting prism, the penta-prism, and other complex prisms, especially prisms having roof edges.

THE GRINDING AND POLISHING OF LENSES.

The methods for grinding and polishing lenses depend to a certain extent on the shape and size of the lenses to be produced. In this section lenses up to 3 inches in diameter only will be considered. The grinding and polishing and figuring of larger telescope lenses is an art in itself which enters but little into the construction of the optical systems required in military instruments intended for field use. In the case of the smaller lenses, 3 inches or less in diamter, flat lenses with surfaces of large radii of curvature are handled differently from lenses with surfaces of shorter radii of curvature, the reason for this being that the flat lenses can be mounted in blocks or shells of the desired radii of curvature whereas the lenses of the second group are commonly of such steep curves that they have to be ground and polished individually.

Flat lenses.

Disks or pressed circular blanks intended for lenses of relatively flat curvature are ground and polished in groups mounted on specially prepared blocks called shells or tools. These tools are made either of cast iron or bronze and are turned to the desired radius of curvature in a lathe or other machine specially constructed for the purpose. For each radius of curvature at least one convex and one concave tool are used and commonly two of each. The convex and concave tools after turning to the desired curvature are ground together with an abrasive in order to render them more accurately spherical. In case the radius of curvature is slightly too long—in other words, the tools are too flat—they are deepened by grinding with a short rocking stroke during the rotation of the tool and polisher; if the tools are too deep, a wide stroke of the upper tool by which it overhangs part of the time well beyond the periphery of the tool below is used. Furthermore if the concave tool is on top serving as grinding tool the radii of curvature of both tools are shortened; if the convex tool is on top, the curvature of both tools is flattened. Thus a flat grinding tool when worked on top of a second tool tends to become concave. On the convex polishers two sets of mutually perpendicular grooves one-fourth inch wide and 1 inch apart are commonly cut across the surface. Generally convex lenses are purposely ground a little flat so that the polishing tool polishes from the margin toward the center of the lens surface. For this reason a slightly larger radius (0.003 inch) is used in the curvature of the grinding tools. The reverse is desired for concave lens surfaces. The radii of curvature of the blocking (polishing) tools are commonly made of the lengths desired for the lens surface.

The lens blanks or flat disks are then cemented or blocked on a concave or convex tool of the proper curvature. (Fig. 82.) To block the lenses they are first heated and a layer of the blocking cement (sealing wax, or rosin and beeswax, or other cement) sufficient to cover the entire lens and still have a thickness of not more than 2 millimeters at its center, is melted on each lens. In blocking convex lenses, a concave supporting tool is employed; its surface is moistened and the lenses are placed on it with the clean surfaces down. A heated convex tool is then pushed against the cement-backed lenses and the lenses are thereby cemented to it. The cemented lens block is mounted in the lens-grinding machine and fairly coarse emery and a high speed of rotation are used. (Fig. 83.) Finer grades of emery are in turn used on the lens surfaces until these are ready for polishing. The curvature of the lens surface is tested from time to time by means of a gauge and slight corrections for curvature are made by regulating the stroke of the grinding tool relative to that of the lens block. The grinding tool itself is reground, if necessary, by means of a fellow

tool of the correct radius of curvature and mounted in place of the lens block. This tool is gauged repeatedly to insure correct curvature.

A polishing block of pitch is prepared by flowing pitch over the tool of the required curvature and impressing on it, while still hot, a fellow tool of equal but opposite curvature. The pitch surface is grooved after the manner of the plane polisher. A long stroke of the polisher is purposely maintained in order to polish the periphery of the lenses first. After the lens surfaces have been well polished, their curvatures are commonly tested by means of standard test surfaces (if possible of quartz); the test surface is pressed against the

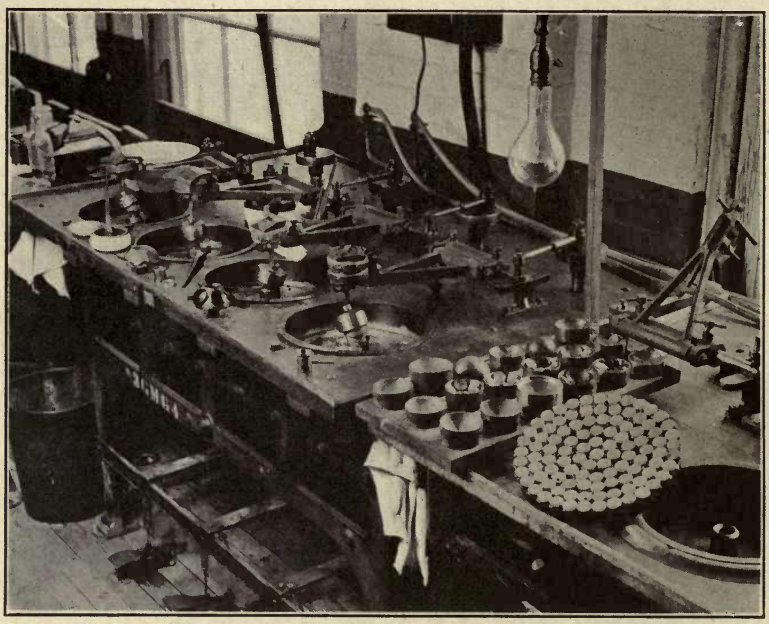


FIG. 82.—The polishing of lenses of medium curvature. Blocks with lenses mounted for polishing are shown in the foreground to the right; also a block of lenses to be polished to a large radius of curvature. (Frankford Arsenal.)

polished lens surface and its relative curvature is determined from the character of the colored Newton interference rings which appear when the examination is made in reflected light. On surfaces to be cemented a tolerance of 8 to 10 fringes is permissible; on other surfaces 3 or 4 fringes is the maximum tolerance. An accurate spherometer of the ring or three-point type with direct reading scale is also satisfactory. As soon as the curvature and polish of the lenses are satisfactory, the lenses are removed from the block by means of a sharp knife or chisel edge inserted into the blocking cement below the lens. The second surface is ground and polished in similar manner provided it is sufficiently flat. The thickness of the lens is gauged

during grinding; for this purpose the tool to which the lenses are cemented must be accurately made and the cementing properly done.

After both lens surfaces have been satisfactorily polished to the desired curvatures, the lens is centered and edged. For this purpose a brass tool of about the same diameter as the lens is required. One end of the tool is turned to a wedge-shaped outer edge, the center being cut to a depth of one-half inch. The lens is warmed and its steeper surface cemented with shellac to this end of the tool, mounted in the axis of a small bench lathe. The tool is rotated and heated by a small flame. The lens is now moved by means of a soft wooden, pronged stick, resting against a support and pressing against the lens surface, until a distant lamp or other object, as seen reflected by the lens surfaces, remains stationary. The lens is now centered and the shellac is cooled by moistening it with water from a sponge. The

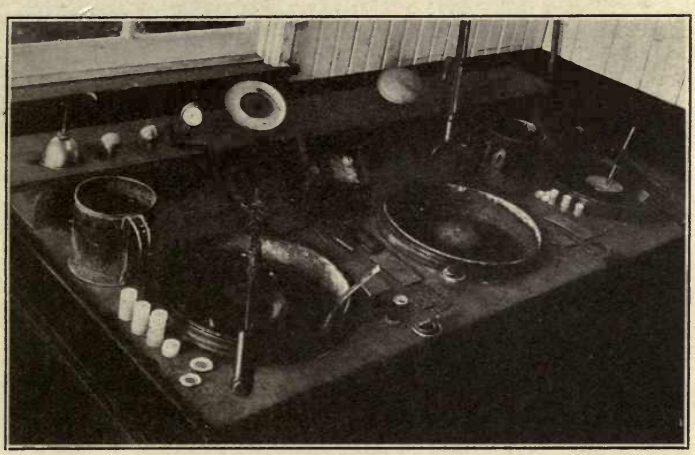


FIG. 83.—Rough grinding of lenses of medium curvature by hand. (Frankford Arsenal.)

edge of the centered lens is turned to a concentric circle by hand by means of a file or diamond point or abrasive lap (fig. 84) or, mechanically, by the use of a rapidly rotating, diamond-charged copper cylinder, similar in character to the milling tools described in a foregoing section. The edging machine is commonly so designed that the diamond charged cylinder is set in action by means of a lever and brought to bear against the edge of the rotating lens, which it grinds then automatically to the prescribed diameter.

LENSES OF STEEP CURVATURE.

Lens surfaces of short radius of curvature are ground separately. Lens blanks in the form of disks with plane-parallel surfaces undergo first a roughing-out operation by which the lens surface is cut out to the approximate degree of curvature. This can be done as a hand operation by means of a file or of a mounted diamond point supported

on a rest, and directed against the slowly rotating glass disk as though it were a piece of metal, or a brass or lead or iron grinding tool of the proper radius of curvature can be used with coarse carborundum and the surface ground out; or a copper spherical tool charged with fairly coarse diamond dust and mounted in a special fixture above an ordinary lens spindle can also be employed and the roughing done with great speed and precision. In the roughing operation care must be taken to keep the edges of the disk of equal thickness; this should be controlled by the use of suitable gauges. The lens after having been roughed out by one of these methods is mounted with sealing wax on a spindle and further grinding and polishing is done on an automatic machine. Bronze grinding tools of the proper curvature are used with the different grades of abrasive.

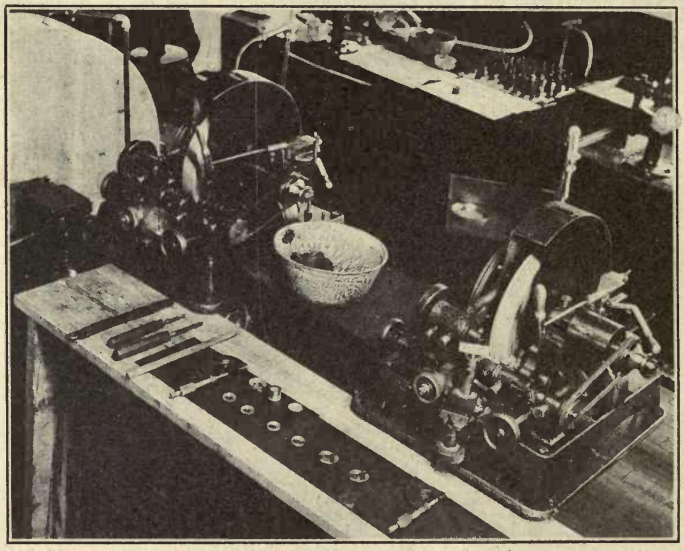


FIG. 81.—Edging and centering machines for lenses. (Frankford Arsenal.)

Pitch polishers, made by pressing the correctly smoothed lens surface or a metal surface of the same curvature against the warm pitch on the polishing tool, are used with rouge. The pitch surface is grooved as usual. The lens is commonly polished nearly to dryness after each wetting. A Newton color test or other gauge (fig. 81) is used to ascertain the curvature. If the polished surface is convex and too flat, the stroke of the polisher should be increased; more grooves may also be cut in the center of the polisher to reduce the bearing surfaces at that point. If the sweep is made too wide the edge of the lens becomes too steep and a "bevel" results. To remove this, the stroke of the polisher is shortened and the lens is polished until it is too low, then the stroke is increased until correct curvature is attained. In case the surface is too high grooves are cut in the pol-

isher near the edge and the length of stroke of the polisher is decreased. If, in this case, the surface is polished down too fast, a "hole" results, the surface is polished low in the center, but remains high near the periphery. Increase of the stroke of the polisher remedies this defect.

Concave surfaces are treated in a similar manner during polishing to correct faults in curvature. Thus, if the radius of curvature is too large, a short sweep is given to the lens and grooves are cut in the margin of the polisher. A longer sweep to the lens and removal of pitch from the central part of the polisher increases the radius of curvature of the concave lens.

Precision polishing is a slow process. At no time should the tool be allowed to heat up appreciably. The speed of rotation should always be slow.

In the absence of automatic spindle machines the grinding and polishing of single lenses can be done by hand on a small bench lathe. The operations under these conditions are learned best by actual xperience. After some training, operators can produce by hand from 20 to 50 lenses per week. The work is necessarily slow and exacting, and with careless operators accidents may occur at any time to ruin a lens on which a considerable amount of work has been put.

THE GRINDING AND POLISHING PROCESSES.

It is of interest to consider briefly the mechanics of the grinding and polishing processes. These have been studied in some detail by J. W. French,[3] who presents a number of important data as well as certain tentative conclusions. French considers the operations under three heads:[4] (1) Rough grinding or forming, (2) smoothing, (3) polishing. To quote from his paper:

> For the first operation a coarse abrasive, such as carborundum, emery, or sand, is employed. The amount of material removed is very great as compared with the pseudo-polish effect. The object of the operation is to shape the glass roughly by the economical removal of material.
>
> For the second operation finer grades of carborundum or emery are used. As compared with the first operation, the amount of material removed is less and the pseudo-polish effect is greater. The object of the operation is to shape the glass by the fine removal of material, both as regards final angle and size. So fine is the surface produced in practice that the size is not generally reduced in the succeeding polishing operation by more than 0.01 millimeter and the change of angle due to the actual production of the polished layer can be controlled within a very few seconds over a length of 25 millimeters.
>
> In both first and second operations the abrasive may be used in loose form and applied with a lubricant such as water by means of a surface grinding tool, usually of coarse-grained cast iron, or it may be in the form of a grinding wheel.

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[3] Some notes on grinding and polishing. Trans. Opt. Soc. London, 17, 24–64, 1916; 18, 8–48, 1917; see also Lord Rayleigh, Proc. Opt. Convention, 1905; Nature 48, 526, 1893; 54, 385, 1901; W. Rosenhain, Trans. Opt. Soc. London, 11, 112–123, 1910.

[4] Trans. Opt. Soc. London, 18, 9, 1917.

Operations (1) and (2) differ only in degree and might be regarded as one stage.

When manufacturing large quantities of the same piece supplied as molded blocks of approximately the correct size and shape, the finest grades of abrasives may be used in the first operation and the pieces may be formed to the final dimensions both as regards size and angle. As the limits of dimensions imposed may be as small as one-thousandth of an inch, and the limit of angle one minute, that is, one three-thousandth of an inch, it will be evident that modern optical work is comparable with good mechanical work as regards dimension, and that an equipment of precision tools is necessary for the so-called roughing shop.

For the smoothing operation under the circumstances above mentioned the same fine grade of abrasive may be employed. The purpose of the operation is then to correct any minute irregularities over the surface of the block of prisms after the individual parts have been laid down and cemented. The purpose is not to control the size and angle.

The grinding process consists chiefly of a chipping out, by conchoidal fracture, of small or large fragments of glass. Certain corners and edges of the grains of the abrasive on rolling about in the grinding operation bear momentarily the weight of the grinding tool and communicate it to the glass surface on which they rest. The larger the grains the less the number that bear the load and hence the heavier they press on the supporting glass and the larger the chip broken out from the glass. The momentary application of a heavy load over a small area, such as the edge or corner of a hard grain, sets up in the glass intense shearing stresses which exceed the elastic limit of the glass and cause it to fracture. The area under pressure is so small that during the short time of the action of the load only a small volume of glass is affected and hence only a small chip is broken out. The greater the load per unit area the larger and deeper the chip broken out. Glass is so brittle that there is little, if any, cutting such as occurs in a malleable metal, like copper, when turned in a lathe. It might be considered that the action of the abrasive is in part a scratching action, plowing up furrows or grooves in the glass; but if scratches on glass surfaces be examined under a microscope the effect is seen to be essentially a chattering or succession of conchoidal or shell-like fractures.

For successful grinding it is essential that the abrasive be hard, that it maintain its sharp corners or edges, and that it does not cleave readily into thin flakes, which obviously are not suitable abrasive agents.

French [5] found that "abrasion depends quantitatively upon the number of points brought into action in unit time, so that the more frequently the grains are brought into repeated action, the greater will be the material removed. It is customary, therefore, to move the grinding tool relatively to the glass, and the amount of abrasion will depend upon the relative speed of the tool and glass." French determined by a series of experiments that with a given speed and a

[5] Trans. Opt. Soc. London, 18, 17, 1917.

given size of fresh abrasive applied at intervals of one minute on a given kind of glass surface, the abrasive effect or amount of glass removed in unit time varies directly with the load applied; also that, other things being equal, the amount removed by abrasion is directly proportional to the speed of the tool relative to the glass. French [6] states further:

> Water, or other lubricant, plays an essential part in the abrasion of glass. If there is too little water the glass will be deeply cut and possibly crack, and if there is too much water the result will be much the same, at least, so far as cutting is concerned. Under proper conditions the abrasive should be well moistened with water, the grains being separated from one another by a film of liquid. One of the important functions of the water is to equalize the temperature over the surface and thus to prevent rapid local rises at the points of action.
>
> If there is too little water, the particles gather in lumps which deeply score the glass. Owing to the absence of sufficient water, the heat generated at the point of abrasion may rise to such an extent that cleavage takes place. If there is a large excess of water a continuous layer of liquid may exist between the tool and the glass. All air will then be excluded and the load on the tool will be enormously increased. Some particles of abrasive may be forced into the glass or tool; others will be caught by the obstruction and tear the glass deeply as before.

The polishing of the finely ground glass surface is done on a flat tool covered with a layer of pitch, wax, paper, or cloth of different degrees of hardness, and coated with moistened polishing material, such as rouge (finely divided ferric oxide), black oxide of iron (ferrous-ferric oxide), putty powder (tin oxide), chromic oxide, or manganese dioxide. For all precision work a pitch surface obtained by melting the pitch and pressing an optically flat surface against it during cooling is used. Two different stages are distinguished by French [7] in the polishing process, namely, wet polishing and dry polishing.

"The function of the first stage is to remove material; the function of the second is to fill up sleeks." Sleeks are minute markings in the polished surface. In certain operations it is customary to "dry up each wet"; but in other operations dry polishing is done only at the end of the wet polishing stage.

French emphasizes the fact first noted by Lord Rayleigh [8] that a few seconds after the finely ground surface has been rubbed on the pitch surface with rouge and water, small, nearly perfectly polished areas appear on the glass surface; in 10 minutes 80 per cent of the surface is polished; but several hours are required to obtain perfect polish over the entire surface. To quote further from French's article:

> If the polished patches are carefully examined under the miscroscope with suitable illumination, there will be observed numerous grooves of different depths, the majority being just invisible. The deeper grooves are typical sleeks, the others possibly

[6] Loc. cit., p. 18, 1917.
[7] Trans. Opt. Soc. London, 18, 23, 1917.
[8] On polish, Proc. Optical Convention, 1905.

embryo sleeks. Frequently the appearance resembles that of a fresh varnished surface over which a fine brush has been drawn. There seems no doubt that the material from the grooves and sleeks is actually removed and not deposited again in the wet polishing stage. From the average of one large series of mesurements the the reduction of thicknesss of a plate of crown glass during each hour of wet polishing by machine was about seven wave lengths. From similar tests made with a thoroughly cleaned old pitch polisher, using water only without any polishing medium, other than that embedded in the skin of the polisher, the amount removed was 2.5 wave lengths per hour. In the third series of tests made with a new black pitch polisher containing no rouge and supplied only with water as a polishing medium the removal of material per hour was two wave lengths. Throughout all these tests the tool was kept continuously wet. It was never allowed to become dry. Before each of the tests the tools were worked down to the true figure of the surface, so as to insure action over the whole face.

With regard to the dry polishing it is customary in practice to dry up the wet—that is, to allow the water to dry and the rouge to be worked out into the grooves provided for it. The glazed-pitch surface then comes into actual contact with the glass surface, upon which it appears to exercise a considerable liquefactive effect and drag, as is to be expected. All the minute furrows produced in the wet stage are leveled down and the sleeks are filled in. The chief function of the operation is to fill in the sleeks and improve the brilliance of the surface. With one forward and one backward stroke by hand over a length of about 15 centimeters a transverse sleek having a width of two wave lengths can be filled in. Two strokes are required for one of four wave lengths. When each wet is dried up the amount of material removed is slightly greater than in the case of wet polishing alone. Thus, in a series of tests with the old pitch polisher already mentioned, using water only during the wet stage and drying up after each wet, an additional three-fourths wave length was removed per hour. The general conclusion is that most material is removed in the wet stage and that a small amount is also removed in the dry polishing stage.[9]

From the foregoing experimental evidence French concludes that polish consists essentially in a dragging off or removal of glass surface by local surface flow of the glass. The depth of the sleeks or furrows left by a flowing particle of rouge was found on measurement to be about eight wave lengths. This result indicates that the surface layer thus affected locally by the polishing action (Beta layer of French) is a film of appreciable depth. Polishing according to this conception signifies the gradual removal of successive surface layers of glass to a plane below the bottom of the deepest pit in the finely ground surface.

By a series of interesting experiments on surface fracture French has been able to show the influence of the Beta film. More data are required to determine definitely the exact significance and extent of the surface flow in polishing, especially with regard to the ability of the glass surface to flow into existing pits or depressions in the ground surface after the manner of the Beilby layer in metals. Suffice it to state the actual data of observation by Lord Rayleigh and French are fundamental to any mechanical explanation of the glass-grinding and glass-polishing processes.

[9] J. W. French, Trans. Opt. Soc., 18, 24–27, 1917.

THE CEMENTING OF LENSES.

After the centering operation the lenses are ready for cementing. Canada balsam is the cement usually employed for the purpose. In thin films it is practically colorless and for most lenses is satisfactory for a period of time at least. The fact, however, that Canada balsam is not a chemical compound but a mixture of essential oils (turpentines, 24 per cent, and rosins, in part soluble in alcohol, 60 per cent, and in part insoluble, 16 per cent) renders its use a matter of nice manipulation. The turpentine oils, volatile at a low temperature, may be distilled off by heating the Canada balsam in a flat dish over a steam plate with or without the addition of a vacuum chamber. Canada balsam thus hardened is most conveniently kept in short, straight-walled glass tubes, about 1 inch in diameter and 3 inches long, with a flat bottom. A short wooden rod inserted into the Canada balsam while still soft serves as a handle for the balsam stick.

The cementing of lenses and prisms is best done in a separate room held as dust-free as possible. Electrically heated plates are commonly used for heating both optical parts and the Canada balsam. Pasteboard or paper covers are used to shield the work from dust.

Before cementing, all glass surfaces are thoroughly cleaned with alcohol and dusted with a fine camel's hair brush. Place the glass elements on a sheet of clean paper on an electric plate and heat up slowly. Do not heat so hot that the paper is scorched. When the glass surfaces are sufficiently hot rub over them the stick of Canada balsam or apply hot Canada balsam which has also been heating on an electric plate. All prism surfaces should be blocked up to a horizontal position in order that the cement will spread out evenly over the entire surface. In the case of lens elements both the concave and convex surfaces should be treated with the balsam. The element with the convex surface is then grasped in a pair of warmed tweezers, with ends bent to conform to the curvature of the lens, and is placed on top of the concave lens element. The two are then pressed and rubbed together to squeeze out as much of the excess balsam as possible and allowed to cool. The cemented lens is cleaned with kerosene or alcohol and ether; a second reheating, sufficient to soften the balsam slightly, is common practice, after which the lens is pressed against an angle block to insure the centering of the cemented elements. In place of the angle block an optical system may be used by means of which a distant cross or a cross from a collimator is imaged by the heated lens in the front focal plane of an eyepiece at which a cross hair is mounted. The lens is centered when the imaged cross coincides with the cross hairs.

For mounting complex prism groups, such as range-finder eyepiece prisms, supporting glass side plates are employed and optical methods

serve to indicate when the several prisms are in satisfactory adjustment.

In all work with Canada balsam scrupulous cleanliness is essential. Care must be taken not to heat the Canada balsam too hot, otherwise it discolors badly; also not to heat the lenses too hot, otherwise bubbles may form in the balsam film which are not easily pressed out. The Canada balsam, if used in the natural condition and not as hardened balsam, is generally heated for a period of time at a low temperature to drive off the more volatile turpentine oils; after mounting with soft balsam the lenses are baked at a low temperature for some hours. The softer the balsam and the lower the baking temperature, the longer the baking period. Electrically heated ovens are best suited for the baking operations

Chapter VI.

THE INSPECTION OF FINISHED OPTICAL PARTS AND SYSTEMS.

The grinding and polishing department of an optical shop is concerned only with the shapes and sizes, but not with the optical performance, of the lenses and prisms which it produces. It is responsible for: The kinds of glass employed, polish and curvatures of lens surfaces, thickness of lenses, centering of lenses and cemented lens combinations, polish and flatness of prism surfaces, prism interfacial angles, dimensions of prisms. The gauges and other testing divices used in the shop serve the purpose only of measuring the external shapes and dimensions of the individual lenses and prisms. In this department the glass is treated throughout, as is brass or other metal in a machine shop, as a substance on which certain mechanical operations have to be performed to produce pieces or parts of prescribed sizes and shapes.

The assembly department, on the other hand, is interested not only in the mechanical features of the lenses and prisms, but also in their optical performance. The apparatus and methods required for testing the optical qualities of a lens, a prism or an optical system are entirely different from the devices for measuring length, thickness, and curvature as employed in the grinding and polishing department and merit special description. In the present chapter some of the approved methods for ascertaining the optical qualities of a lens, prism, and complete optical system will be described briefly. A general statement only can be given with special emphasis on the underlying principles.

During the war it became necessary, in certain cases, for Government inspectors to pass upon the separate elements of an optical system as well as upon the finished optical instrument. This situation arose because of the fact that here and there throughout the country there were lens-grinding establishments, chiefly spectacle-lens manufacturers, that might be able to produce the optical parts for certain instruments, but not the mechanical parts; on the other hand there were also available precision mechanical shops not fully occupied with war work that might produce the mechanical parts. The situation was not without its troubles, because there was an

inevitable tendency on the part of each manufacturer, the optical and the mechanical, to shift the blame for lack of proper performance of the optical parts on the other fellow. The manufacturer of the optical parts sought to obtain as large tolerance limits as possible in order to attain maximum production with the least trouble and expense. The manufacturer of the mechanical parts, on the other hand, sought to establish as narrow tolerance limits as possible on the optical parts and thus to avoid trouble and expense in the optical assembly room; in general he did not realize the need for some adjustment in the assembly of the mechanical parts, because of the extreme difficulty in manufacturing interchangeable optical elements. To secure the best results from an optical system slight shifts in relative positions are generally necessary, and this means fitting the mechanical parts to the optical. The ideal system, and the system to which the manufacturer of precision metal parts is accustomed, is to make each part to a standard size with a small tolerance limit definitely fixed by gauges, and then to assemble the different parts without much special fitting. In the case of optical elements small changes in the refractivity or in the degree of curvature of the lens and prism elements may produce relatively large changes in the final result, such that some relative adjustment of the different optical parts is necessary; these necessitate slight changes in the mechanical arrangements. To this kind of work the manufacturer of the mechanical parts is not accustomed; and, if he undertakes to assemble the instruments in final form, a specially trained group of assemblers for the optical and mechanical parts is essential.

Adjustment and fitting of the mechanical parts of an instrument in order to get the best results from a given optical system is considered necessary even in optical instrument factories of long experience. This is still more essential in the case of spectacle-lens manufacturers who, in war time, are willing to try to make precision optics; but are not properly equipped to do so and may not have had adequate experience to realize the significance of precision work. It requires patience, tact, and nice discrimination on the part of the Government inspectors under such conditions, discouraging alike to the manufacturer of the optical parts and to the instrument maker, to keep up the interest and to establish in a short time production in both factories on a satisfactory routine basis. In general it is good policy to place orders for optical instruments of high precision with firms experienced in their construction, the firm receiving the contract to make and to be responsible for the entire instrument. For low power, visual instruments separate contracts may be let for the optical parts and for the mechanical parts, the final assembly to be done preferably by the maker of the mechanical parts.

In contracts of this kind definite tolerances, both optical and mechanical, for each part of the optical instrument should be stated specifically; these are determined not only by the kind of optical system desired, but also by the mechanical adjustments available for the final mounting of the optics. In certain instruments the mechanical arrangements are such that only small variations in the lenses, especially in the focal length, are permissible, whereas in other instruments large variations in focal length are tolerated and, except for a slight change in the total magnification, do not materially affect the performance of the optical system. In fire-control and other measuring instruments the tolerances are more exacting than in instruments intended for observation purposes only. Nice discrimination and wide experience are required to prepare fair and adequate specifications for the several optical elements of a given lens system. The tolerances should be so set that every optical element, which will function satisfactorily in the complete instrument, is passed and each optical element, which will not so function, is rejected.

METHODS FOR THE INSPECTION OF THE COMPONENT PARTS OF AN OPTICAL SYSTEM.

There are in general two different groups of methods available for the inspection of an optical system and its component optical elements; these methods may be termed "direct" and "projection." Observations by the first group of methods are made with the aid of auxiliary optical instruments and apparatus and the defects of a given optical element or optical system are ascertained by direct inspection. The continued use of optical instruments for inspection is, however, tiring. In many cases projection methods of inspection have been used to advantage, whereby the optical element (lens or prism) or the image, formed by it, is projected on a suitable screen where it can be viewed in enlarged form and the departures from set standards read off directly on easily legible scales. The eyestrain under these conditions is appreciably less than in instrumental observations with auxiliary telescope or microscope and the readings may be made more rapidly. In this chapter a general outline only is given of the several available methods of inspection for detecting a particular optical defect in a lens or prism or optical instrument. No attempt is made at completeness either in citing all available methods or in describing any given method in detail. To do this would require a separate volume.

THE INSPECTION OF LENS- AND PRISM-ELEMENTS OF AN OPTICAL SYSTEM.

Inspection of lenses for size and shape.—The thickness of a lens through the center is measured by means of a screw-micrometer gauge, a vertical comparator, a spherometer, or some similar device. The diameter of the lens is measured by means of a screw-micrometer gauge or of two ring gauges, the first, a go gauge which determines the maximum permissible diameter, the second, a no-go gauge which prescribes the minimum diameter. The curvatures and sphericity of the lens surfaces are measured by means of one of several types of spherometer or by the use of standard test surfaces, or of circular gauges or templets cut out of sheet metal or of glass. Mechanical tests of this kind are so familiar that further description is unnecessary.

Inspection for physical defects in a lens.—These include: (*a*) Bubbles, stones, laps, folds, and other pressing defects; (*b*) striae; and (*c*) strain. For the inspection of the first group of defects the lens is placed on a piece of black cloth and is illuminated by a strong light from the side as in figure 65, page 206. In an objective and in other lenses mounted at a distance from the image plane a few small bubbles are tolerated and do no appreciable harm; but in eyepiece field lenses, reticules, and any other optical elements which are located in the image plane or in its conjugate planes, bubbles are not tolerated because they appear in the field of view and may cause trouble in a military optical instrument. Lenses containing stones or crystallization bodies should be rejected. The presence of a pressing defect is commonly sufficient cause for rejection; but in certain cases a small, faint fold at the edge of a lens may not appreciably affect its optical performance. Heavy ribbon striae in a lens should not be tolerated; objective lenses exhibiting single-thread striae are generally accepted. In most cases of striae, the ultimate criterion is not the presence of striae but rather the optical performance of the lens under conditions of test arranged to render its defects easily discernible. Strain is tested by examination of the lens in polarized light. In order to attain uniform illumination of the lens it is customary to employ a point source of light at the rear focal plane of a well-corrected collimator lens and to place a polarizing prism either in front of the small aperture or to reflect the parallel rays from the collimating lens on a flat, opaque, polished glass surface at the polarizing angle. The lens to be examined is placed either at right angles to, or parallel with, the beam of polarized rays and is viewed through an analyzing nicol and sensitive tint plate and the strain distribution is thereby ascertained. The lens should not be held in the fingers longer than necessary during the test because of the strains introduced by local heating.

Under these conditions the lens appears to be best illuminated when the observer's eye is placed at its rear focal point. In the case of a concave lens, it is advantageous to shift the collimator lens or to add a second condenser lens in order to produce sharply convergent polarized light, part of the convergence of which is then neutralized by the negative lens under test.

Routine inspection, by projection methods, of lenses for certain physical defects has been practiced for many years in certain optical shops. During the war these methods were widely adopted and with much success. The lens under inspection is illuminated by a strong source of light (fig. 85), and is in turn imaged by a good photographic lens on a dull-white flat screen of drawing paper, or of finely ground opal glass; for certain purposes an undeveloped photographic plate or a carefully faced magnesia block serves as a screen. The screen should be of fine texture without markings of any kind. The en-

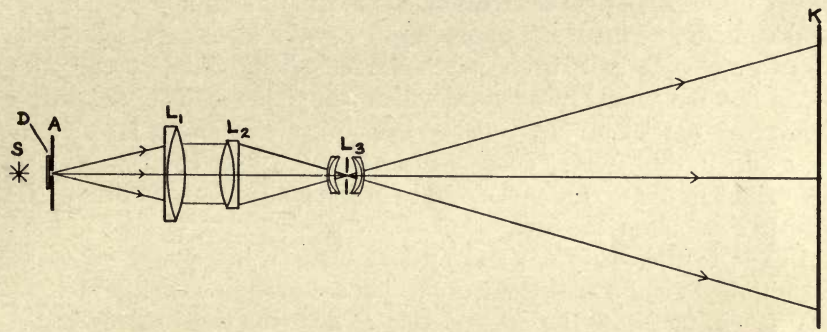

FIG. 85.—Projection method for the inspection of lenses. *S* is the source of light; *D*, diffusing screen; *A*, a pinhole aperture; L_1, condenser lens; L_2, lens to be inspected; L_3, projection lens; *K*, projection screen.

larged image of a lens illuminated, as indicated in figure 85, shows clearly physical defects, such as bubbles, stones, pressing defects, and striae. By racking the photographic lens in and out, different planes in the lens under inspection can be imaged on the screen and every part of the lens then inspected. At the same time surface defects, such as pits and scratches, and insufficient polish, are imaged on the screen and the lens can be inspected for them. By closing the diaphragm of lens L_3, figure 85, and shifting the lens L_2 or L_3 slightly, oblique illumination is obtained and aids in rendering faint striæ visible.

A photographic plate and camera may be substituted for the projection screen and a permanent record of the results of inspection of a particular lens can be thus obtained. The defects illustrated in figures 7, 8, and 9 were photographed in this manner. Similar photographs have been taken before; recently Smith,[1] Bennett, and

[1] T. T. Smith, A. H. Bennett, G. E. Merritt, Characteristics of striae in optical glass, Bureau of Standards, Scientific Paper No. 373, 1920.

Merritt have published excellent photographs of striae in optical glass, taken by this method, which is essentially that of a special optical system illuminated properly.

Mechanical defects.—The lens surfaces are examined with a magnifying glass for pits, scratches, sleeks, grayness, and insufficient polish, chipped edges, and cracks. Illumination from the side by an intense light source is advisable. Wavy or double-curvature polish should not be present; this is commonly first detected in centering the lens.

Cemented lenses are inspected for bubbles and blisters in the cement film, for color of the Canada balsam, and for the presence of particles of dirt or of fuzz from the cleaning rag in the balsam.

The projection method of inspection described in the last section is suitable for detecting mechanical defects in a lens.

Optical qualities.—Lenses may be inspected for focal length, accuracy of centering, and quality of image with respect to definition or resolution, spherical aberration, coma, astigmatism, distortion, and achromatism. There are many methods available for ascertaining these properties and, in a particular case, the simplest and most direct method should be adopted which will yield results of the desired degree of precision. In routine inspection the effort is made to ascertain if the several characteristics of the lens come within the prescribed limits so that on assembly in the instrument it will function properly as one of the integral parts.

In the testing of lenses and optical systems in general, there are certain devices and arrangements which are used in so many methods that it will facilitate the presentation to describe them briefly at this point. These include artificial stars, distant targets and scales, collimators, and collimating devices.

Artificial stars are set up as distant point sources of light and serve especially in tests of the optical performance of telescope objectives and telescope systems. Small silvered glass globes, globules of mercury, or small illuminated pinhole apertures in opaque screens located 30 or more feet away, depending on the focal length of the objective from the observer, are used for the purpose. For many purposes an artificial star illuminated by a monochromatic illuminator is convenient for testing chromatic aberrations or the change in performance of a lens with change in wave length of light. As source of light a lamp with concentrated tungsten filament or tungsten bead or a Nernst filament is convenient. A condenser lens may also be used to advantage.

Distant targets are commonly painted with black or colored lines on a white background. Scales, vertical and horizontal, of definite intervals are thus prepared; also systems of coordinate lines, mutually perpendicular and definitely spaced; also diagrams of lines or sectors radiating from a common center. Targets of this kind are generally

erected 100 or more feet away from the observer and are useful for testing the performance of military optical instruments.

Test plates, either of sheet metal with small holes and slit and cross-slit openings cut into them, or of silvered glass plates with sets of parallel, definitely spaced lines cut with a dividing engine, and small circular holes, or a photographic negative with similar sets of lines are especially useful for measuring the optical quality and the resolving power of an objective or a complete telescope. The metal test plate should be several feet square and should be placed in a window 50 or more feet distant; its perforations are illuminated by skylight. The other test plates are much smaller and have much finer lines. They are illuminated from the rear by a strong source of light and a condenser lens, and are placed 30 or more feet away from the observer.

A collimator is widely used for routine factory inspection and is a convenient substitute for the distant target or test plate. It consists essentially of a well-corrected telescope objective mounted at one end of a telescope tube, at the other end of which is placed an opaque plate with small circular aperture located at the rear focus of the collimator objective and illuminated by a lamp or bulb. For certain purposes an astronomical telescope objective, 4 or 5 inches in diameter and of long focal length, is used with a small test plate of silvered glass placed at its rear focus. On the test plate are ruled with a dividing engine sets of definitely spaced lines, both vertical and horizontal; also a group of lines diverging from a common center, and several small circular holes of different diameters. The test plate may be 1 inch in diameter and, if the objective of the collimater is of the best quality, serves for testing most of the defects in an optical system. Collimators are compact testing devices, and, were it not for the fact that the images which they form are encumbered with the defects introduced by the collimator objective, they would be even more extensively used than at present; for many purposes collimating telescopes are entirely satisfactory, not only for the inspection of optical elements, but also for the adjustment of optical instruments.

Measurement of focal length and external focal length of a lens.— The measurement of the equivalent focal length or of the external focal length (back focus) of a lens suffices in many instances to determine the degree of accuracy of the curvature of the lens surfaces. If the focal length is correct, it may be assumed that the lens surfaces are approximately correct. This applies especially to cemented doublets and other combinations.

Many methods are available for measuring the equivalent focal length of lenses and are described in detail in textbooks on optics. For work of precision an optical bench with the necessary accessories

is essential; on it the four principal Gauss points, namely, the two foci and the two principal (and nodal) points are commonly determined with reference to the vertexes of the two external surfaces of the lens or lens combination. A distant artificial star illuminated with strong white light or with monochromatic light commonly serves as test object in these measurements. The exact positions of the principal foci are determined by means of an auxiliary microscope; the positions of the nodal points are ascertained by rotating the lens about a vertical axis and noting that when the axis of rotation coincides with a nodal point, the image of a distant object remains stationary during the rotation of the lens through an appreciable angle.

A critical test for zonal variations in equivalent focal length, for spherical aberration, and for other axial aberrations of a lens is the Hartmann [2] method of extra-focus measurements as modified by

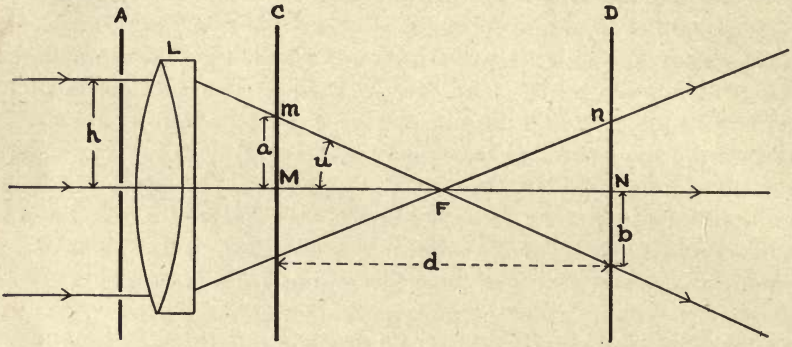

FIG. 86.—Hartmann-Tillyer test for the aberrations in a positive lens or lens combination.

Tillyer.[3] For the Hartmann-Tillyer test a metal disk perforated along one or more diametral lines by a set of definitely spaced holes (1 millimeter in diameter and 3 millimeters apart for lenses of fair size) is placed in front of the lens or objective to be tested (fig. 86), so that monochromatic light from a distant artificial star on entering the objective is restricted to a definite number of small pencils. Two shadow photographs are taken, the one at some distance inside the focus of the lens, the second outside the focus. Each ray pencil forms a small disk on the photographic plate. The exact positions of the ray-pencil disks are accurately determined and from these, together with the distance of separation of the photographic plates, the points of intersection of the rays on the axis can be computed. The distance between these points is the spherical aberration. The angle u which a paraxial pencil entering the objective at a height h

[2] Zeitschr. Instrumentenkunde, 24, pp. 1, 33, 97, 1904.
[3] Jour. Wash. Acad. Sci., 3, 481, 1913; Nat. Bur. Standards, Sci. Paper No. 311, 1917.

above the axis can also be computed from the data of measurement and found to be

$$\tan u = \frac{a+b}{d}$$

wherein a and b are the distances from the axis of the disks formed by the ray pencil on the two photographic plates separated by the distance d. The equivalent focal length is then

$$f = h/\sin u$$

Tillyer has shown that if the positions of the holes on the screen are known to within 0.005 millimeter, the equivalent focal length for the particular zone can be determined by this method with an average error of 0.05 per cent. The variation of the focal length with different zones of the objective is a measure of correction for the sine condition. By using lights of different colors (monochromatic illuminator, cadmium spark) it is possible also to measure the chromatic aberration.

A method for ascertaining the exact focus of a lens is the Foucault or "knife-edge" method; this method is based on the fact that in a well-corrected objective the rays are sharply focussed at a point, and radiate as an evenly illuminated cone on either side of the focus. If now a knife-edge be brought slowly across the line of sight at the exact focus directly in front of the observer's eye the illumination of the objective is cut off abruptly as the knife-edge crosses the axis. In case the lens is not well corrected either spherically or chromatically, there is no position at which the illumination disappear; suddenly; either the inner or the outer portion of the illuminated lens disk becomes dark first and the lens appears unequally illuminateds in case white light is used the disk appears differently colored for different positions of the knife-edge along the axis.

By mounting the lens under test as the objective of a telescope with an astronomical high-power eyepiece and viewing the changes in the image of a distant artificial star when the eyepiece is pushed in and out, the observer can locate the exact position of focus and at the same time determine in a satisfactory manner the extent to which the several aberrations in the lens under test are corrected. In case the lens is well corrected the image of the star appears as a small circular disk of light uniformly illuminated. Its diameter is least at the position of exact focus. In the case of spherical aberration the illumination of the disk is not uniform, the central area of the disk being brighter for one position of the eyepiece, the outer portion for another position. By using different colors of lights and observing the shapes of the disk in different parts of the field the observer can determine the optical performance of the lens with a high degree of accuracy.[4]

[4] This method is described in detail by H. D. Taylor, in The Adjustment and Testing of Telescope Objectives, published in 1896 by T. Cook, of York, England.

During the war a great many photographic lenses were inspected by means of a distant artificial star (pin hole aperture in front of a monochromatic illuminator) used in conjunction with a precision optical bench constructed in the shape of a T. The lens is mounted on the bench in a holder of the iris diaphragm type and can be rotated, and also slid back and forth in its carriage which is supported on a pillar mounted on a slider which can be moved along the head or cross arm of the T-shaped bench. Along the vertical arm of the T-bench a second pillar is provided which supports an observing microscope and is mounted in a carriage which slides along this arm. The angle of rotation of the lens in its carriage can be read off on an accurately divided circle; the transverse movement of the lens can be read off accurately by a micrometer screw. The observing microscope consists of an 8-millimeter apochromatic objective with compensating eyepiece and cross hairs; its movement in the sliding carriage can also be read off with high precision by micrometer screws.

With this bench the Gauss points are first located for the wave length 550 millimicrons (yellow-green color). The character of the image produced by the rays from the distant star (10 meters distant) entering the lens at different angles (in steps of 3° from the axis) is studied and the positions of the radial and tangential astigmatic lines as well as the circles of least confusion are ascertained for different colors. From these measurements the astigmatic differences are read off directly; also the degree of flatness of the field, the distortion, and the chromatic differences of magnification. For the oblique rays a correction is applied to allow for the flat plate. Coma is judged from the character and width of the image of the star for different positions of the lens. From the appearance of the star image alone, as formed by the photographic lens in different positions, the inspector is able to form a correct estimate of the quality and type of the lens. In the hands of a competent inspector this method proved exceedingly useful and satisfactory.

For the testing of photographic lenses a chart method [5] may also be used to advantage but it is less rapid than the foregoing.

For ordinary routine inspection of lenses intended for military optical instruments, which are for the most part instruments of low magnification (4 to 12 power) the foregoing methods are unnecessarily refined. For most purposes it suffices to measure the external focal length (back focus); this is the distance from the principal focus to the vertex of the nearest lens surface. This can be done rapidly and with sufficient exactness by placing the lens under test in a ring mount as the objective of a telescope, by setting in front of the telescope a collimator having at its rear focus a small test plate with sharp lines or patterns drawn upon it on which the observer can focus

[5] A chart method of testing photographic lenses, L. E. Jewell, Jour. Opt. Soc. America, II–III, 51, 1919.

sharply. The image of the test plate, as formed by the lens under test, is brought to sharp focus by racking a high power astronomical eyepiece or an observing microscope in and out, its position is read off directly on a suitable scale, so adjusted that the readings give directly the external focal length (back focus) of the lens. Rotation of the ring mount with the lens about its axis is a test for the centering of the lens. If the lens is decentered the image is seen to describe a circle during the rotation, the amount of movement depending on the eccentricity of the lens. After a small amount of practice on an apparatus of this kind, the observer is able not only to measure the external focal length rapidly and accurately and to test for centering, but also to measure the resolving power or definition of the objective and to detect spherical and chromatic aberration, coma, astigmatism, and distortion. For this purpose the test plate should have ruled on it sets of equally spaced vertical lines, also several horizontal lines and small circular holes. In general, however, it is advisable not to attempt, in routine inspection, to measure more than the external focal length and to test for centering on a collimating device of this kind. During the measurement an estimate can be made of the general quality of the image formed and of the degree to which the lens is corrected for the several aberrations; but no actual measurements of these factors are made.

In an optical system the defects of one lens are compensated by equal and opposite defects in other lenses; thus the individual lenses of a system may show pronounced aberrations whereas the completed system is entirely satisfactory. In order that there be a proper compensation of errors between the several components of a system, it is essential that the specifications laid down by the designer be accurately followed; if the focal length or external focal length of each element is correct, it is generally safe to assume that the specifications have been so followed.

In place of the collimator a system of inspection may be adopted whereby the image, formed by the lens of a test plate, is projected on a screen. For the purpose a silvered glass plate on which two sets of equally spaced, mutually perpendicular lines are ruled with a dividing engine is most satisfactory; less satisfactory, but still serviceable is a photographic reproduction (negative) of a suitable drawing of coordinate lines. The test plate is illuminated by parallel rays from a strong, point-source of light at the rear focus of a well corrected condenser lens which covers the entire test plate. The rays emerging from the test plate are practically parallel; the rays from any particular point of the plate pass as a narrow pencil through a small part of the lens, with the result that the image points on the screen are formed by the convergence of narrow bundles of rays, thus reducing the effects of spherical aberration and coma. A sharp image is

formed and a correspondingly accurate setting can be made for the determination of the focal length. The definition on the screen decreases from the center outwards because of astigmatism and curvature of field. An estimate of the amount of spherical aberration and coma present in the lens is obtained by placing back of the test plate a ground glass or opal glass diffusing screen which destroys the parallelism of the rays emerging from the test plate. Decrease in definition, under these conditions, at the center results from spherical aberration, while in other parts of the image it results from astigmatism, coma, and other defects. When the test plate is moved a definite small amount in a direction transverse to the axis of the lens, the image is shifted by an amount which depends on the focal length of the lens; and from this the focal length can be computed. The other aberrations are estimated from the appearance of the image on the screen. If the two sets of mutually perpendicular lines can not be simultaneously focussed astigmatism is present; if the lines on the margin of the image are curved, distortion is present. Simple apparatus suitable for the testing of lenses and prisms by this method was devised by the Ordnance Department and found to be satisfactory for practical testing at Frankford Arsenal.

Another method for ascertaining the properties of a lens is to use the metal plate target, described in a foregoing paragraph; the target should be set up at a distance of 100 or more feet from the lens to be tested. The lens is placed in a mounted ring and functions as the objective of a telescope. Its external focal distance, centering, and other properties are then ascertained by the methods described above for the collimator method, except that in this case a correction must be made because the object is not at an infinite distance. For routine inspection, however, where definite tolerances are set this correction is taken into account in the scale used with the eyepiece or the reading microscope.

The resolving power is ascertained by this method by sighting upon sets of equally spaced lines drawn on a test plate located at a definite distance, 30 feet (10 meters) or more, and illuminated by a strong light. The spacing of the finest set of lines which can still be distinguished as distinct lines determines the angle which is resolved by the objective. An auxiliary reading microscope is commonly used in the examination of the image formed by the objective. Theoretically the angular separation of two fine lines or stars which can be imaged as distinct elements by a lens of diameter d is approximately equal to the angle subtended by the wave length of light at a distance equal to the diameter of the lens. For two stars which can be just resolved by a telescope objective the formula derived from the theory of diffraction for the angular separation in radians is

$$\frac{0.61 \cdot \lambda}{r}$$

wherein λ is the wave length of light and r the semidiameter of the lens; to reduce this to seconds of arc divide by 0.0000048; or more directly it is $127000 \cdot \lambda/r$. For a wave length $\lambda = 0.00055$ millimeter near the middle of the visible spectrum, this expression reduces to $70/r$ seconds of arc as the theoretical resolving power of a telescope objective of semidiameter, r, expressed in millimeters. This degree of resolving power is rarely achieved by objectives for military optical instruments. Generally the resolving power of a telescope system equal to 1 minute of arc divided by the magnification is considered to be an upper tolerance limit; commonly it ranges from 35 to 50 seconds of arc divided by the magnification.

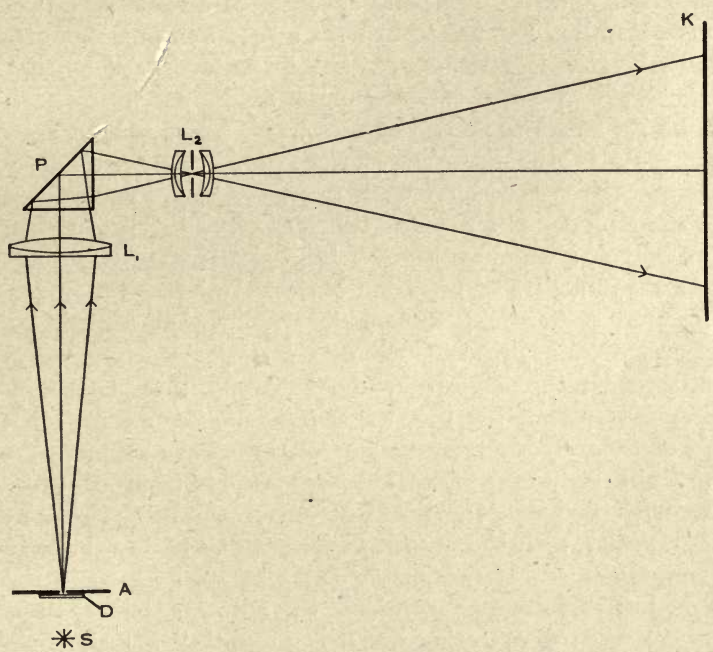

FIG. 87.—Projection method for prism inspection. *S* is the source of light; *D*, ground-glass diffusing disk *A*, pinhole aperture; L_1, achromatic doublet; *P*, prism under test; L_2, projection lens; *K*, projection screen.

The inspection of prisms.—Prisms, like lenses, are inspected for defects in the glass, such as stones, bubbles, striae, strain, and color; for external dimensions; for mechanical defects, such as lack of polish of surfaces, presence of pits and scratches, degree of flatness of surfaces and accuracy of interfacial angles; for optical qualities, such as distortion and deviation of transmitted light rays from the prescribed paths.

The examination for stones, bubbles, and pressing defects is best made under conditions of illumination from the side (dark-ground illumination); striae are detected by any one of the methods described in the foregoing section on lenses. These defects can also be seen to advantage by projecting the prism on a screen by the projection

method described above. This projection method was widely adopted for routine factory inspection during the war and proved to be satisfactory. The optical arrangement for the purpose is shown schematically in figure 87. Prisms are inspected for strain by the standard methods which have already been described.

The dimensions of the prisms are measured either by means of calipers or of sets of standard gauges. Interfacial angles may be measured mechanically by standard angle gauges. For inspection purposes it is preferable, however, to test the optical performance of the prism rather than to measure interfacial angles.

The degree of flatness of the prism surfaces is best tested against that of a standard optically flat plate accurate to a tenth or a twentieth of a wave length. For most purposes a prism surface flat to one or two wave lengths is satisfactory; but in prisms, such as the Dove inverting prism (vertical rotating prism in the panoramic sight), in which the light rays are reflected at a large angle, a slight departure from flatness in the reflecting surface may cause an appreciable warping of the reflected light-wave front and thus impair the definition of the image. The reflecting surface of such a prism should be flat to a part of a wave length over its entire area.

In the manufacture of precision optics, a tolerance of $\pm 2'$ of arc is considered a fair and reasonable specification for most prism angles. In certain prisms, such as the Dove erecting prism and the pentaprism, the angle must be correct within $\pm 1'$ of arc; in the roof-angle prism, the roof angle must be correct within a few seconds of arc. These prism-angle tolerances are commonly measured optically and the specifications are stated in terms of permissible angular deflections of transmitted rays from the prescribed paths.

In conformity with the practice adopted at Frankford Arsenal, on the recommendation of Col. G. F. Jenks in 1910 for the inspection of the optical performance of prisms, the following conventions may well be followed: A reflecting prism in an optical instrument serves to change the direction of the optical axis of the instrument through a definite, prescribed angle. Let the plane in which this angle is measured be called the "axial plane." Then the "axial-angle error" of a prism placed with its reflecting surface in the correct position is the angular component, in the axial plane, of the deviation of the reflected ray, after emergence from the prism, from the prescribed path. The "side-angle error" is the angular component, in the plane normal to the axial plane, of the deviation of the reflected ray, after emergence from the prism, from the prescribed direction. The Dove erecting prism serves only to invert and not to change the direction of the axial rays after emergence; for this prism which presents a limiting case, let the axial plane be perpendicular to the hypothenuse surface and to the first surface entered by the incident ray;

it is the plane of incidence of the incident rays and contains the normals to the incident refracting surface and to the hypothenuse surface. These conventions establish the reflecting surface of a prism as the surface of reference. Any other surface might be used, but for the sake of uniformity in the testing and designation of the different types of prisms the reflecting surface appears to serve the purpose best. In the case of roof-edge prisms and pentaprisms two reflecting surfaces replace the single reflecting surface and serve to invert the image; in these types of prisms the two reflecting prisms function as a unit and may be treated as such.

Experience has shown that different optical methods of different degrees of sensitiveness may be used to test the optical performance of any given type of reflecting prism. The deviations should be measured of those rays which traverse the prism along the path which they follow in the actual instrument; in other words, a measure of the actual performance of the prism should be taken.

In view of the fact that the path of a ray through a prism depends on a number of different factors, such as defects in the glass, degree of flatness of prism surfaces and in addition to different interfacial prism angles, the only feasible method for computing the deviations of transmitted axial rays from the prescribed path, which result from slight departures of the several prism angles from the prescribed angles, is to consider the glass to be free from defects and optically homogeneous and the prism surfaces to be optically flat. Under these assumptions it is possible to ascertain the competency of the several different optical methods available for testing and to determine the significance, in terms of actual prism angles, of different optical tolerances which may be set. The relations between actual prism angles and the resulting ray deflections in the axial and side (normal to axial) planes are indicated for the different types of prisms in figures 88 to 94. In these figures a section of the correct prism is indicated by dotted lines; the incorrectly oriented surfaces are indicated by full lines; the paths of the rays are indicated by full lines with arrow marks. In each set of curves the ordinates are the angles of departure, t, of the prism surface from which the ray emerges; the abscissae, the deviations, d, of the emergent ray from the prescribed path; the series of oblique lines represent the departure angles, s, of the incident prism surface.

THE RIGHT ANGLE REFLECTING PRISM.

Three optical methods may be used to test this type of prism; in two of the methods a telescope and distant target or collimator are employed; in the third an autocollimator serves the purpose. A variation of these methods is obtained by the use of a projection screen in place of the observing telescope.

FIRST METHOD.

Axial angle errors.—Let it be assumed, for the sake of simplicity, in this and other cases of axial angle error that the faces of the prism are in the same zone—i. e., all vertical to the same plane; this is practically the case in all prisms and the slight departures from this condition introduce departures of the second order only, in the axial angle errors. Let s be the error of the angle (positive if the total angle exceeds 45°) which the first side face includes with the hypothenuse (fig. 88) and t the error of the second side face. These errors are always small and do not exceed 10 minutes even in very poor work. The deviation of the emergent ray from its prescribed path in the axial plane is $d=(n-1)\ (s-t)$, wherein $n=1.515$ is the refractive index of the prism. In figure 88 the deviations of the rays are represented by the abscissae, the angles t by the

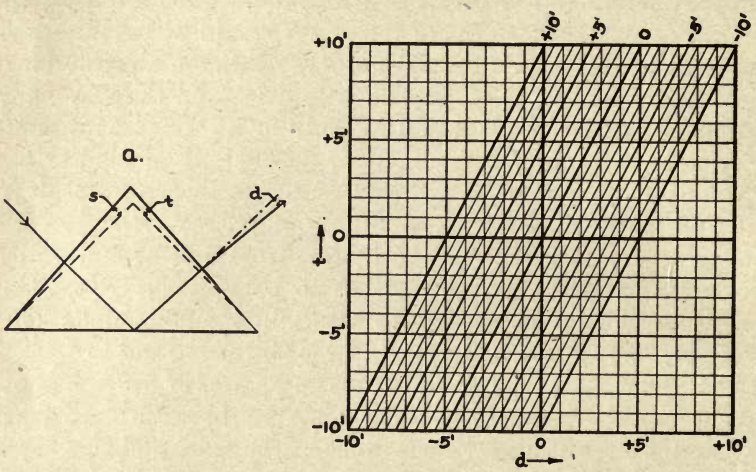

FIG. 88.—In this diagram are given the deviations of the emergent ray, from the prescribed path, after transmission through a right-angle prism of slightly incorrect interfacial angles as indicated in fig. 88*a*.

ordinates and the angles s by the series of oblique lines; thus a prism for which the first interfacial angle is 45° 02′ ($s=+2'$) and the second interfacial angle is 45° 01′ ($t=+1'$) causes a deviation of the emergent ray in the axial plane of $-\frac{1}{2}'$ from the prescribed path.

Side-angle errors.—In this and other cases of side-angle errors the angles which the side faces include with the hypothenuse face are considered to be exactly 45°. This assumption is made in order to facilitate the computation; the error introduced by it is of the second order only because the departures in these angles from 45° are very slight. In this method the incident ray enters along the normal to the first side surface, is reflected at the hypothenuse face, and is then refracted at the second side surface whose trace on the hypothenuse face includes a small angle t with the trace of the first side surface on the hypothenuse. Under these conditions the deviation of the

emergent ray for a prism of refractive index, $n=1.515$, is $d=1.07t$; in other words, the deviation is practically equal to the departure angle, t.

With this method, therefore, the angular deviation of the emergent ray from the prescribed path, both in the axial plane and the side plane, is of the same order of magnitude as that of the errors in the interfacial angles, and the method is not especially sensitive. The method has the advantage, however, that the prism is tested under conditions resembling those of actual use.

For routine testing by this method either a spectrometer or a combination of a telescope of adequate resolving power and a collimator or telescope and distant target is used. The prism is placed with the hypothenuse surface against a fixture having rounded bearing points for both the hypothenuse and first side surface. The fixture is accurately adjusted so that the plane of incidence contains the normals both to the hypothenuse face and to the first side face. A coordinate scale in the image plane of the telescope indicates the axial and side angle departure from the prescribed path. In place of the observing telescope a projection screen with properly arranged coordinate lines to mark the tolerance limits may also be used.

SECOND METHOD—THE CONSTANT DEVIATION METHOD OF FRANKFORD ARSENAL.

Axial-angle error.—The paths of the rays through the prism when used as a constant deviation prism are shown in figure 89. The incident ray is considered to be perpendicular to the hypothenuse face. The deviation, d, of the emergent ray from 90° is then $d=2\ s+(i-r)-(i'-r')$, wherein i is the angle of incidence, r, the angle of refraction, and $\sin i=n \sin r$, $(n=1.515)$; r' is the angle of incidence of the emergent ray and equal to $(r-3s-t)$, and $\sin i'=n \sin r'$. The deviations d for different values of t and s are shown by the curves of figure 89. From these curves it is evident that in a prism whose angles differ from the correct angles by $\pm 2'$, the maximal deviation of the emergent ray from the prescribed path may be $d=11'$. The curves show, moreover, that if the prism is observed only in one position, this method may not be adequate to determine its quality; thus for $s=0'$ and $t=+10'$ the deviation is $+9'$; if now the prism be reversed so that $s=10'$ and $t=0'$ the deviation is $d=-46.5'$. It is thus evident that unless care is taken to measure a prism from both directions erroneous conclusions regarding its quality may be drawn from the result obtained. If, moreover, the incident ray enters at a different angle from normal to the hypothenuse face slightly different deviations result. The deviation depends therefore not only on the prism-angle errors but also on the position of the prism during the observation. The last uncertainty

is eliminated by prescribing that the incident ray shall coincide in direction with the normal to the hypothenuse face.

Side-angle error.—Let the prism side angle be 45°; let the direction of the incident ray coincide with the normal to the hypothenuse face; let the plane of incidence include the normals to the first side face and to the hypothenuse face; let t be the angle between the traces of the first side face and of the second side face, respectively, on the hypothenuse face. The deviation d of the emergent ray from the prescribed path is then approximately $d=-t/2.1$ for $n=1.515$; in other words the deviation is about half that of the angle t and the method is not especially sensitive in this respect.

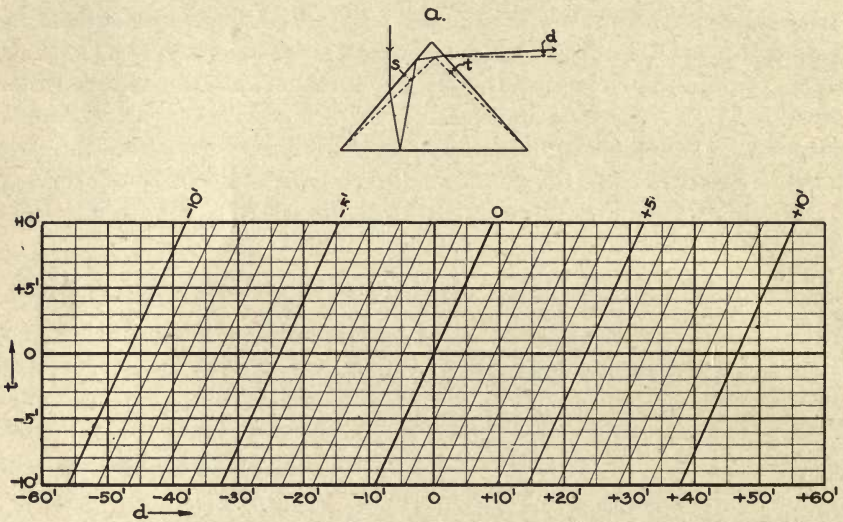

FIG. 89.—*Constant deviation method.* In this figure the deflections are shown of the emergent ray from the prescribed path, after transmission through a prism of slightly incorrect interfacial prism angles, as indicated in fig. 89*a*.

THIRD METHOD—AUTOCOLLIMATION METHODS.

Axial-angle error.—In these methods a well corrected autocollimator of adequate resolving power is used; the hypothenuse surface is placed at an angle of 45° with the axis of the collimator. (Fig. 90*a*.) The deviation of the emergent ray from the original line of sight is then approximately $d=2nt-2(n-1)s=3.03t-1.03s$ for a prism of refractive index $n=1.515$. The curves of figure 90 show that for errors in the prism interfacial angles of $s=+3'$ and $t=+1'$ the deviation $d=0$; for $s=-3'$ and $t=+1'$ the deviation is $d=+6'$. The method alone is therefore not adequate to test the prism angles. If, however, the prism be rotated and the hypothenuse face be placed normal to and facing the collimator (fig. 91*a*), the curves of figure 91 show that the deviation, as computed from the formula $d=2\ n\ (t+s)$, for $s=+3'$ and $t=+1'$ is $d=+12'$; for $s=-3'$ and

$t = +1'$ the deviation, $d = -6'$. The measurement of the deviations of the prisms in these two positions suffices therefore to measure the angles satisfactorily. The autocollimation method is much more sensitive than the first method and is less encumbered with defects than is the second method.

Side-angle error.—With the prism placed in the position of figure 90*a* the side-angle deviation is practically the same as that obtained in the first method, namely, $d = 1.07 \cdot t$ or $d = t$ approximately.

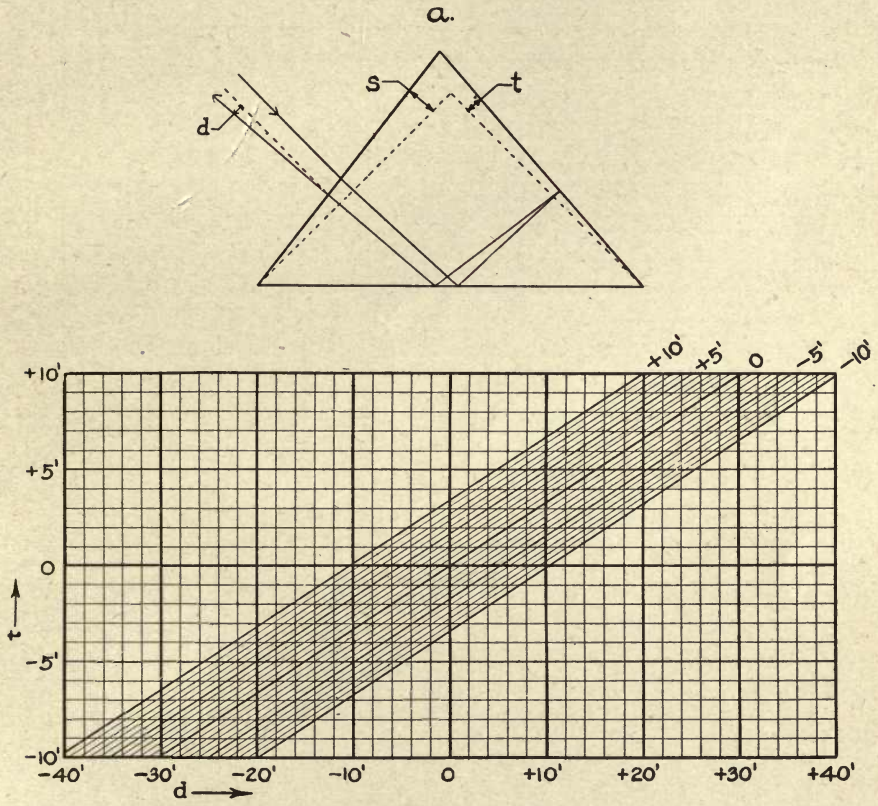

FIG. 90.—*Autocollimation method.* In this diagram are shown the deviations of the emergent ray from the prescribed path, which on transmission are produced by slight departures *s* and *t* in the interfacial prism angles from the correct angles, as indicated in fig. 90*a*.

A projection method may also be used with autocollimation, but this method is simply a modification of the telescope methods and involves nothing new in principle.

THE DOVE ERECTING PRISM.

Vertical rotating prism of panoramic sight. This prism is in effect a truncated right-angle prism, but it is used to invert the image and not to change the direction of an axial ray in the telescope.

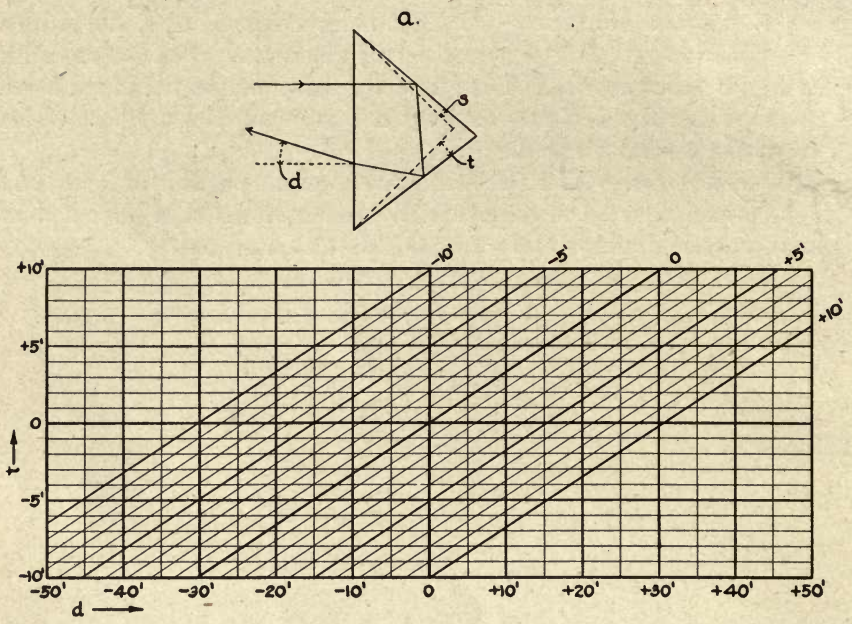

FIG. 91.—*Autocollimation method.* A graphical representation is given in this diagram of the deviations of the emergent ray from the prescribed path, after transmission through a prism of slightly incorrect interfacial angles, as indicated in fig. 91*a*.

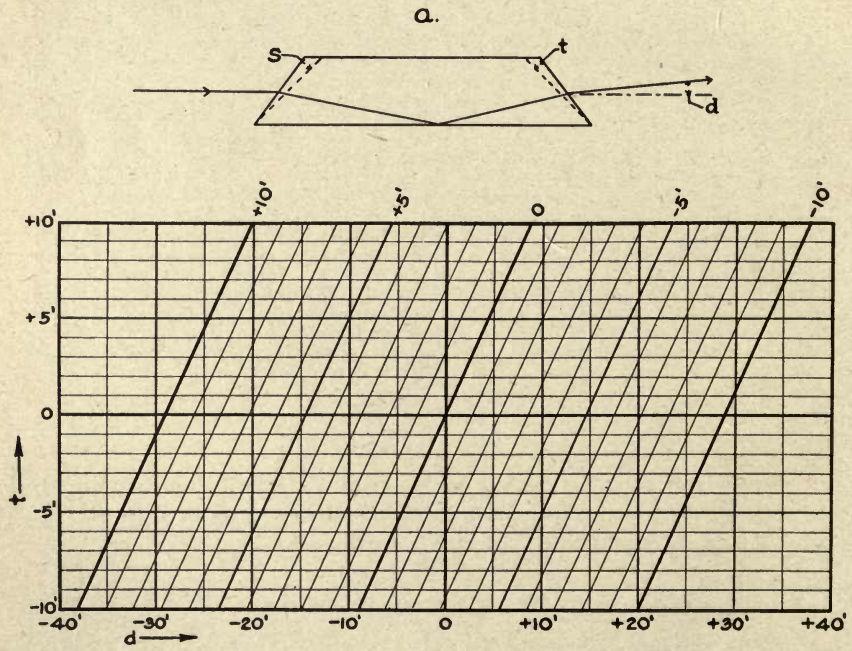

FIG. 92.—In this figure the deviations are shown of the emergent ray from its prescribed path, after transmission through a prism of slightly incorrect interfacial angles, as indicated in fig. 92*a*.

In the method commonly used for testing this prism a collimator or distant target together with an observing telescope with coordinate scale in its image plane is employed. The prism is placed in front of the telescope with the hypothenuse face parallel with the line of sight.

Axial-angle error.—The path of the axial ray through the prism is shown in figure 92*a*. The deviation d for prism interfacial angle errors s and t is $d=45°-t-i'$ wherein $\sin i'=n \sin r'$; $r'=r+s-t$; $\sin (45°-s)=n. \sin r$ and $n=1.515$. The curves of figure 92 show that for $s=+1'$ and $t=-1'$, $d=-3.8'$; for $s=+3'$ and $t=+10'$, $d=0$; but if the prism be reversed so that $s=+10'$ and $t=+3'$, the deviation $d=-26'$. In testing a prism by this method, therefore, it should be examined in both positions, otherwise serious errors may arise. This fact should also be noted in the assembly of the prism; as for example, in the assembly of the vertical rotating prism in the panoramic sight.

Side-angle error.—On the assumption that the side angles are correct and equal to 45° and that the axial plane is normal to both the hypothenuse and first side faces, the trace of the second side surface on the hypothenuse face includes a small angle t with the trace of the first side face on the hypothenuse face, the resulting side-angle deviation of a transmitted axial ray is approximately $d=-t/2.1$ for $n=1.515$.

THE ROOF-EDGE PRISM.

This prism may be treated as a simple reflecting prism in which the hypothenuse reflecting surface has been replaced by two reflecting surfaces mutually at right angles and truncating, like a roof, the elongated edges of the hypothenuse face. The roof angle must be exactly 90° within a few seconds of arc, otherwise a double image results. The incident light strikes the first reflecting surface at an angle of 60°, is reflected across to the second face, and is reflected by it at an angle of 60°, thus inverting the image completely. The tests for axial-angle and side-angle errors may be made by the methods used for ordinary reflecting prisms; of these the autocollimating methods appear to be the most satisfactory. The correctness of the angle is determined by the absence of a double image of the lines on the horizontal line of the target. The following rule is useful in determining, in the case of a double image, whether the roof angle is greater or less than 90°. Rack the eyepiece of the observing telescope inward; if the two images approach each other the roof angle is less than 90°; if they approach when the eyepiece is racked outward the roof angle is greater than 90°. Another method for testing the roof angle is to grind and polish a small face truncating the edge between the two side faces of the prism; a ray of incident light normal

to this face should be reflected by the roof faces as a single ray parallel with the original direction. This test is made with an autocollimator; the method is, however, hardly to be recommended, as it offers no advantage over the foregoing method and requires the preparation of an additional face on the prism.

THE PENTA PRISM.

Methods similar to those described in the foregoing paragraphs are used for testing pentaprisms optically. In all cases the prism should be held against a proper fixture so that the incident ray enters normally to the first surface of the prism as indicated in figures 93*a* and 94*a*.

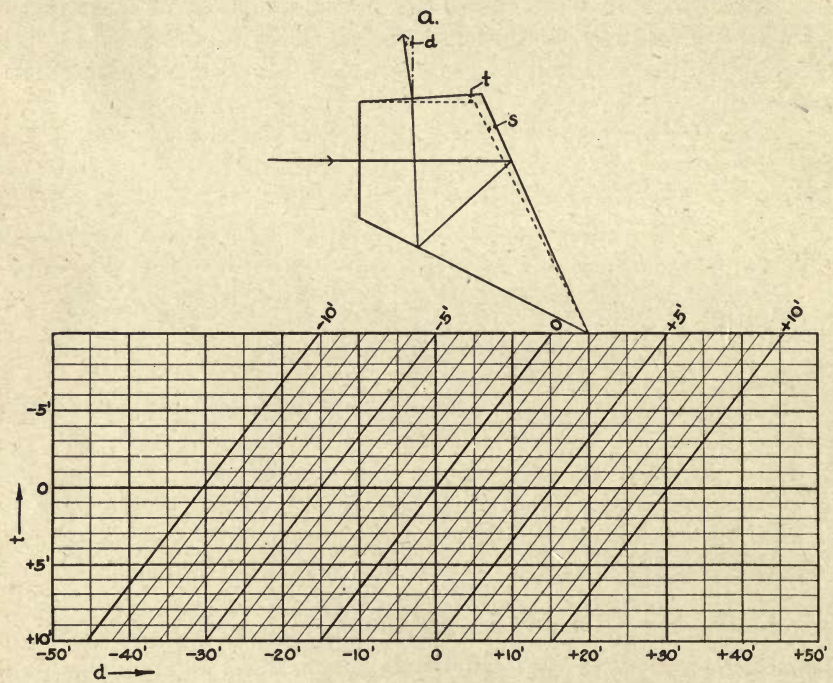

FIG. 93.—In this diagram the deviations are represented of the emergent ray from the prescribed path, after transmission through a penta prism of slightly incorrect interfacial prism angles, as indicated in fig. 93*a*.

First method.—A collimator or distant target with horizontal and vertical lines is used in conjunction with an observing telescope or projection screen.

Axial-angle errors.—For a ray entering the prism normal to the first face as shown in figure 93*a*, the deviation of the emergent ray from the prescribed path is $d=n(2\ s-t)$, wherein t and s are the small angular errors in the interfacial angles of the penta prism, and $n=1.515$ is its refractive index. The series of curves in figure 93 are a graphical solution of the foregoing equation; thus for $t=+2'$, and $s=-1'$, $d=-6'$; for $t=+2'$, $s=+1'$, $d=0$. The equation

shows, moreover, that a slight change s in the angle between the two reflecting faces has twice the effect in deflecting a transmitted ray that the same change t has in the angle between the other two faces. The reflecting faces here function as a unit just as do the reflecting faces of a roof edge prism.

Side-angle error.—Let the line of intersection of the two reflecting faces include an angle t with the line of intersection of the two other faces. This gives a twist to the prism. Let the angle between reflecting faces be 45° and that between the other two faces, 90°. The angle of deflection is approximately equal to $d=n.t$, wherein $n=1.515$, the refractive index of the glass.

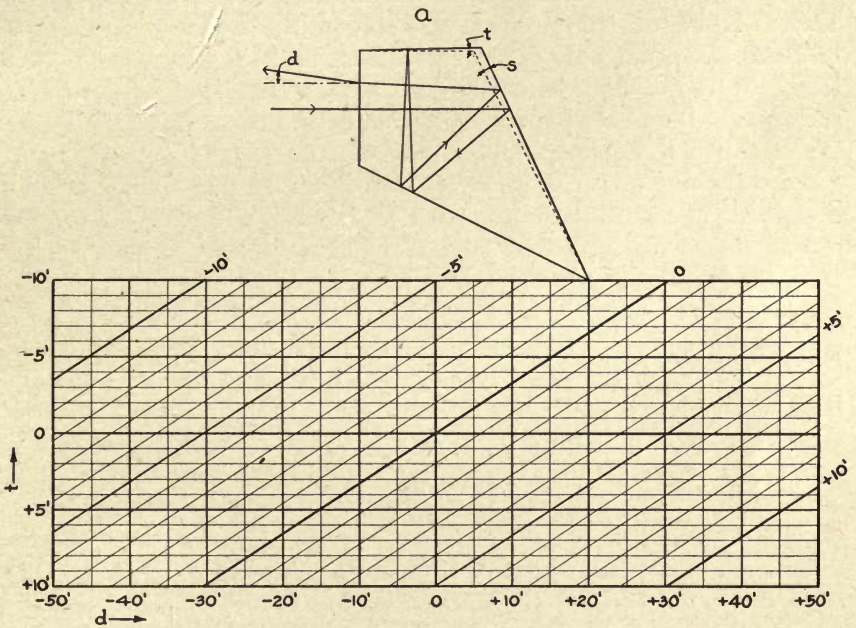

FIG. 94.—*Autocollimation method.* In this diagram the deviations are shown of the emergent ray, from the prescribed path, after transmission through a penta prism of slightly incorrect interfacial prism angles, as indicated in fig. 94*a*.

Autocollimation method—Axial-angle error.—The deflection in this case (fig. 94) is $d=2n(2\,s-t)$ or twice that obtained by the first method; thus for $t=+2'$ and $s=-1'$, $d=-12'$; for $t=+2'$ and $s=+1'$, $d=0$. Similarly the side-angle error is approximately twice that found by the first method. The results prove, however, that in these methods a compensation may take place whereby zero deflection may be obtained from a prism whose angles are incorrect.

The interfacial angles of these prisms may also be measured directly on a large, specially designed fixture which is essentially a part of a large spectrometer equipped with well-corrected telescope objective lenses, 3 inches in diameter (theoretical resolving power about 2 sec-

onds of arc); as source of illumination in the collimator a fine silk fiber or spider web illuminated by a strong light from the side may be used in place of the slit.

For the testing of a right angle an optical square is useful. It consists of two plates of glass or quartz mounted together by optical contact; the one plate is polished optically flat on one surface; the second thick plate has at least two optically flat, mutually perpendicular surfaces. One of these surfaces is placed in optical contact with the surface of the first plate. The edge of the second plate is truncated slightly before mounting in order to facilitate the cleaning of the edge of the finished optical square. The prism to be tested is placed with its side faces in contact with the faces of the optical square. The interference fringes formed between the several faces are a measure, then, not only of the correctness of the right angle, but also of the degree of flatness of the surfaces as compared with that of the standard optical square. The making of a correct optical square is a task which requires a high degree of skill.

The resolving power of prisms is tested in a manner similar to that described for lens; a distant target, consisting of a plate ruled with sets of fine, equally spaced lines and illuminated by a strong light from the rear, or a collimator with a similar but smaller test plate in its rear focal plane, is examined through the prism with a well-corrected telescope. The resolving power is then the angle subtended by the spacing of the finest set of lines which can be seen as distinct lines when viewed under these conditions. In case a prism is to be used in front of an objective, as in a battery commander's telescope or a range finder, its resolving power should be at least equal to that of the objective. By examining, through a high-power telescope, the effect which the prism exerts on rays from fine lines and holes in a distant metal plate target or from a test plate in a collimator, the inspector can determine the optical quality of the prism as regards astigmatism, coma, distortion, achromatism, and the like. If the prism functions properly under these conditions of severe test, it will do so in the optical system for which it is intended.

THE INSPECTION OF OPTICAL SYSTEMS.

In this section a brief outline only is given of the several factors which enter into the inspection of a completed optical system. No consideration is given to the functioning of an optical instrument as a measuring device of precision; and only a selected few methods for determining certain optical characteristics of a complete optical system are described in a general way. To do more than this would lead too far. Many military optical instruments, especially ordnance instruments, are telescopes, and these only are considered in the

following sections. In Chapter II, an outline is given of the functions of a telescope and of some of the factors with which the designer and manufacturer have to contend in order to attain the desired results as laid down in the specifications. These cover commonly the following items: Size of entrance pupil or objective aperture; size of exit pupil; eye distance or distance of exit pupil from rear of eyepiece lens; magnifying power of telescope; angular field of view, apparent and actual; resolving power; quality of image with reference to color corrections, to definition in different parts of the field, to distortion, and to other defects; percentage light-transmission of the optical system; polish of lens and prism surfaces and presence of film.

Most of these properties can be determined either by the use of auxiliary telescopes and measuring apparatus or by projection methods in which the image is projected on suitable screens by means of suitable auxiliary lenses.

Diameter of entrance pupil and of exit pupil.—In Chapter II the functions of the several diaphragms in an optical instrument are described briefly. The aperture of the lens system determines the relative amount of light which can be received from a distant object point; the aperture in a telescope depends not only on the diameter of the objective, but also on the diaphragms in the telescope. The larger the aperture the more light enters the instrument and the finer the detail which is imaged distinctly; also the shorter the depth of focus. The entrance pupil of the telescope is by definition the smallest diaphragm visible from an object point toward which the axis of the telescope is pointed; similarly the smallest diaphragm visible from the corresponding image point is the exit pupil. Entrance pupil and exit pupil are conjugate with reference to the telescope and the one is the image of the other by the lens system. Moreover the ratio of the diameter of the entrance pupil to that of the exit pupil is directly a measure of the magnifying power of the telescope.

In the design of a telescope the size of aperture is determined by the normal resolving power and the magnification desired; in military optical instruments intended for field use the diameter of the exit pupil should be about 5 millimeters. In few military instruments, with the exception of range finders, is the full resolving power utilized. For naval and other instruments, such as musket and machine-gun telescopic sights, required for use on a moving platform, an exit pupil of 7-millimeter diameter is desirable; but this can be attained only at the sacrifice of other desirable qualities. In case the exit pupil is much larger than the iris of the eye, the image appears to jump as the eye occupies different positions in the exit pupil; strong color fringes are also present in the field.

If the telescope is held at a distance from the observer and pointed at the sky, the exit pupil appears as a disk of light, suspended in

space, back of the eyepiece. Its distance from the eyelens of the eyepiece is the "eye-distance;" when the iris of the observer's eye coincides in position with the exit pupil of the instrument he is able to see the entire field of the telescope. For convenience the "eye-distance" should be at least 12 millimeters; if less than this the eyelashes are liable to touch and brush against the eyelens.

The diameter of the exit pupil may be conveniently measured by means of an auxiliary positive eyepiece mounted in a draw tube together with a fine micrometer scale at its rear focus. The eyepiece is focused sharply on the exit pupil and the diameter of the pupil is read off directly on the micrometer scale. The eye distance is also determined by a scale which is attached to the draw tube and indicates the distance of the micrometer scale from the front of the draw tube or from the rear surface of the eyelens. The diameter of the entrance pupil is ascertained by placing a scale directly in front of the objective and noting the number of divisions included in the image of this scale as seen in the exit pupil. The ratio of these two diameters is the magnification of the telescope.

In place of the eyepiece drawtube attachment the exit pupil may be projected by a lens on a screen and its diameter measured in terms of a scale drawn on the projection screen; similarly the diameter of the entrance pupil can be determined. In all cases the exit pupil should be circular in shape and appear uniformly illuminated.

In telescopes of the Galilean type with a dispersive eyepiece the exit pupil is a virtual and not a real image and can not be measured directly. To overcome this difficulty a positive lens is placed at a distance equal to twice its equivalent focal length from the scale of the eyepiece mounted in the drawtube; a real image of the same size as the virtual image is thereby obtained on the micrometer scale. The eye distance in this case is a negative quantity and is located inside the instrument.

Magnifying power.—As noted in the foregoing section the magnifying power of a telescope is given by the ratio of the diameter of the entrance pupil to that of the exit pupil, and these in turn are determined by the ratio of the focal length of the objective to that of the eyepiece.

Another method for ascertaining the linear magnifying power is to measure the angular vergency of the initial and final zone pencils. For this purpose the angle included at the observer's station between the lines of sight to distant points is first measured directly with a theodolite or transit; the telescope under test is then focused on a distant object and placed in front of the transit with its objective pointing toward the transit; the angle between the same two distant points is remeasured as seen through telescope and transit. The ratio of the tangents of half the angles thus measured is the linear magnifica-

tion. The ratio of the angles directly is the angular magnification. In place of the distant objects a collimator with properly ruled test plate may be used.

The magnification can also be ascertained by a projection method in which the lines on a ruled test plate in a collimator are projected by means of an auxiliary lens on a ruled screen. The telescope with its objective pointing toward the collimator is inserted between the collimator and the auxiliary lens and the change in the spacing of the projected test-plate lines is noted. From the amount of change as measured by the ruled lines on the projection screen the magnification can be determined directly.

Still another method for ascertaining the approximate magnification of a telescope is to view a distant target scale simultaneously with the two eyes, the one eye unaided, the second with the telescope placed before it. The number of scale divisions, as seen by the unaided eye, included between two adjacent scale divisions as seen through the telescope with the second eye, is the magnification.

The real and apparent fields of view.—The actual angular field of the telescope is measured by sighting upon a distant object and observing the angle through which the telescope must be turned in order to bring the image of the distant point from one margin of the field along the horizontal diametral line to the margin on the opposite side. The apparent angular field is obtained by multiplying the angle thus obtained by the magnification. The apparent linear field may be deduced by noting that the magnification is the ratio between the tangent of half the angles of the apparent field and the real field, respectively.

Resolving power.—The ability of the telescope to resolve fine details of an object is a measure of its resolving power. To test its resolving power a silvered test plate, placed at a definite distance from the telescope (10 or more meters) and ruled with sets of equally spaced fine lines and intensely illuminated from the rear, is viewed by the telescope. In order to relieve eyestrain and to facilitate the observations the telescope image is viewed with a low-power auxiliary telescope. The angular equivalent of the spacing between the finest lines, which appear as separate distinct lines under these conditions, is a measure of the resolving power. On a test chart of this kind [6] small pinhole apertures are generally included as artificial stars. From the changes in appearance of the image of an artificial star as the eyepiece is racked in and out and as the telescope is rotated slightly so that the star appears in different parts of the field, conclusions may be drawn regarding the degree of correction of the several aberrations, such as spherical aberration, chromatic aberration, coma, astigmatism, distortion, etc.; also flare and double images. A good

[6] T. T. Smith, Jour. Opt. Soc. America, II–III, 76, 1919.

telescope should resolve without difficulty lines separated by an angle equal to 60 seconds of arc divided by the magnification. In many telescopes the resolution is 40 seconds divided by the magnification.

Quality of image.—To test the optical performance of a telescope lens system a number of different methods are available. One of the simplest of these is the distant artificial star test, especially if the star be illuminated with different monochromatic lights. An auxiliary telescope magnifying 4 or 5 diameters may be used in the tests to magnify the eyepiece image. The test for spherical aberration is to rack the eyepiece in and out and to note that in a spherically well corrected lens system the disk of light is circular and evenly illuminated on both sides of the image plane; if spherical aberration is present the center of the disk is brighter on one side of the image plane while the periphery is brighter on the other side. Coma is recognized by the appearance of a one-sided flare extending from the star image when it is placed near the margin of the field. Astigmatism may also affect the star image when it is placed near the margin of the field; if astigmatism is present, its effect is seen on racking the eyepiece in and out, whereby the star appears either as a short horizontal or a vertical line when the eyepiece is racked in and as a short vertical or horizontal line when it is racked out. In an intermediate position of the eyepiece the star image appears as a disk of light. Distortion is recognized by a change in the apparent size of the star image in case it is observed first in the center of the field and then at the margin. Distortion is more readily detected by the use of a distant target ruled with equally spaced coordinate lines. The lines near the margin of the field appear then curved; pincushion and barrel-shaped distortion are the two types of distortion which result from the differences in magnification at the center and at the margin of the field. Lack of adequate color correction gives rise to the appearance of a colored fringe around the artificial star, the color differing with different positions of the eyepiece. Curvature of field is recognized by the fact that when the star is in sharp focus at the center of the field, it is not in focus when placed at the margin, but can be sharply focused by changing the position of the eyepiece. Decrease in definition toward the margin of the field may be incorrectly ascribed to curvature of field when it is actually due to the presence of other aberrations, such as astignatism, coma, spherical zones, etc.

Other methods requiring the use of distant targets are in use and are well adapted for inspection purposes but it would lead too far to describe these in detail.

Film and lack of polish on lens surfaces.—These defects are most readily detected by pointing the telescope with eyepiece or objective toward a strong distant source of light and observing the different elements in the telescope not in the direct light, but with the telescope

rotated slightly so that the lenses and prisms appear in half-shadow. Film and poor polish then appear as a slight haze over the surfaces, which with practice can be detected at a glance. During the war much trouble was encountered because of the appearance of film on lens surfaces; the source of trouble was found to be different in different cases. In some instruments unstable glass caused the trouble; in others the film was found to be organic in nature and deposited from volatile matter such as oil, grease, poorly baked lacquer, etc., included in the instrument at the time of its assembly and adjustment. The general conclusion, reached as a result of many researches into the causes of film, has been that only weather-resistant glass of good quality should be used in military optical instruments and that the most painstaking care should be taken in the assembly of optical instruments to insure cleanliness and freedom from grease and volatile matter in the interior of telescope tubes; under no conditions should the operator's fingers touch the lenses and prisms, after cleaning, during their assembly into the instrument. Failure to observe these simple precautions and to provide proper assembly rooms free from dust, was the cause of many rejections of optical instruments, especially binoculars, during the war.

The light-transmission of a telescope depends on a number of factors, such as quality and kinds of glass, total glass path, number of reflecting surfaces, quality of polish of the surfaces, condition of Canada balsam layer in cemented lenses. There are available different methods for measuring the light-transmission of telescopes; several of these were described in Chapter IV and need not be repeated here. They are without exception photometric in nature. The essential difference between determining the light-transmission of a piece of glass and a telescope is that in the telescope the rays follow prescribed paths whereas in the glass plate they may be transmitted along any direction.

For the measurement of the transmission of a telescope it is essential that the light rays follow a telecentric course and that the exit pupil of the telescope be imaged in the field of the photometer. A simple attachment to the Koenig-Martens polarization photometer [7] is shown in figure 71, page 214. It consists essentially of an achromatic lens mounted in a brass cylinder which slips over the front tube of the polarization photometer and images the exit pupil or entrance pupil of the telescope in the field of the photometer. The lens is so placed that the front aperture of the photometer coincides with its rear focal plane. Either the objective or eyepiece end of the telescope may face the photometer. The source of illumination is the same as that described in Chapter IV; also the method

[7] F. E. Wright, Jour. Opt. Soc. America, II–III, 65, 1919.

of measurement in which the position angles of the analyzer in the photometer are recorded for settings with the telescope in the field and for settings without the telescope. The ratio of the squares of the tangents of the angles thus obtained is a measure of the percentage light transmission of the telescope.

A photometric bench may also be used to advantage for measuring the percentage light transmission of telescopes. An instrument of this type was manufactured during the war by Keuffel and Esser (Fig. 69, page 212) for the use of inspectors of optical instruments and proved to be satisfactory in practical work. Another type of bench photometer for the measurement of the light transmission of optical glass and of optical instruments is that described by C. V. Drysdale.[8]

[8] Trans. Opt. Soc. London, p. 100, 1902; 18, 375, 1917.

Chapter VII.

THE OPTICAL INSTRUMENT SITUATION DURING THE WAR.

In the foregoing chapters a general description is given of the processes of manufacture of optical glass and of the optical parts of lens systems. Emphasis is placed on those processes which were developed during the war period and proved to be suitable for use in an emergency. No picture is, however, given of the development of the optical situation, as a whole, and of the measures taken to meet the ever-increasing demands of the Army and Navy for military optical instruments. As a matter of record a brief sketch is presented in the present chapter of the progress made and of difficulties overcome. In retrospect and with the facts before us it is now a simple matter to state how this and that should have been done; but at the time decisions had to be made on the fragmentary evidence available. The records show, that, although there was much waste effort and confusion, the Army and Navy were actually supplied with most of the optical instruments which they needed; also that Army and Navy at maximum strength in 1919 would have been adequately equipped with fire-control and other optical instruments.

The development of the optical-glass situation is briefly described in Chapter I. Several details may be added here to illustrate the kinds of problems which arose and the manner in which they were solved. These included problems of factory organization, of factory operation, of the procurement and transportation of raw materials and of glass melting pots and of coal; also the more difficult task of obtaining hearty cooperation from certain manufacturers who were vitally interested, but who extended formal cooperation only with a strong undercurrent of passive resistance. Cooperation of this kind leads to innumerable delays and unfilled promises and must be treated both tactfully and firmly to accomplish the desired results.

In the game of war-time production everything is subordinated to the one object of producing the desired material within a definite period; the military program requires munitions of many different kinds, and it is the task of the manufacturing forces of the country to furnish these on time. Everything else, including expense, is for the moment, subordinated to speed; as the manufacturing program

gathers momentum, the half-hearted cooperationists either learn their lesson or they are eliminated. Under the stress of high-speed production suggestions and plans for increasing the rate of production are made; and if, after adequate test, these prove to be satisfactory, they are introduced into the factory routine. Many of these suggestions come from outside plants.

Under the emergency conditions many manufacturers of broad vision are willing to exchange information on factory practice with their peace-time competitors with the result that over the entire country the manufacture of munitions soon attains a state of efficient operations.

The procurement and the transportation of the raw materials for optical glass required constant attention throughout the war. At first it was necessary to locate satisfactory sources of supply for these materials. Specifications had to be stated with reference both to the optical glass requirements and to the chemical manufacturing possibilities. Many chemical manufacturing plants were visited by members of the Geophysical Laboratory before the details of the supply of raw materials were properly arranged. The problem of transportation continued to be a constant source of trouble throughout the war period. Innumerable delays in the shipment of raw materials occurred; in many instances the General Munitions Board, and later the War Industries Board and the Production Division of the Ordnance Department rendered valuable service in expediting railway traffic. It is inevitable, however, that in a war-time emergency railway traffic is overtaxed. Under these conditions it is the duty of each manufacturer of munitions to stock, as early as possible, adequate quantities of supplies so that the inevitable delays in the transportation of additional supplies do not retard production. At one time during the early months of the war about 40 manufacturers were actively assisting in the manufacture of optical glass, chiefly in the supply of the necessary raw materials and of glass melting pots.

The question of fuel and gas for the glass-melting furnaces and for other operations became serious during the coal shortage of the winter 1917–18. When it is realized that the glass plant at the Bausch & Lomb factory alone consumed 33,000,000 cubic feet of illuminating gas per month, a quantity sufficient to meet the needs of a city of 80,000 inhabitants, the scale of its fuel consumption and of the difficulty of meeting the situation adequately is apparent.

From April to December, 1917, the efforts of the Geophysical Laboratory were concentrated chiefly on the development of the manufacture of optical glass. By December, 1917, the production of pot optical glass had reached 40 tons per month; at one plant (Bausch & Lomb) the processes of manufacture had been mastered for the most part; and subsequent efforts were directed chiefly to an

increase in the manufacturing capacity for optical glass throughout the country. Early in December the Geophysical Laboratory took charge of the Spencer Lens plant and, as a result of hearty cooperation on the part of this firm and a modern though small plant, was able to produce satisfactory glass from the first melt on. Late in December the Geophysical Laboratory assumed practical charge of the Charleroi plant of the Pittsburgh Plate Glass Co. This plant was an old plate-glass plant in which the Pittsburgh Plate Glass Co. had installed 16 single-pot glass-melting furnaces of a blast-furnace type and had tried unsuccessfully for several years to produce a satisfactory product. At the time the Geophysical Laboratory arrived at the plant several of the problems involved to place the plant on a running basis were not at first apparent, especially the lack of temperature control in the glass-melting furnaces and the impossibility of establishing such control with the system then in operation. The entire battery of furnaces was supplied by air from a single low-pressure line fed by a blower operated on an electric circuit subject to rapid changes in voltage; in this system a change in the flow of air in one furnace affected the rate of flow of air in the remaining furnaces, with the result that violent fluctuations in the temperature of each furnace were the rule. Good optical glass can not be made under these conditions. Each furnace had to be equipped with individual blowers and many fundamental changes effected before satisfactory production could be attained. This required some months for accomplishment and proved to be a task of considerable difficulty, partly because of a lack of appreciation on the part of this company of the significance of the factors underlying the manufacture of optical glass and of the fact that optical glass is not plate glass, nor is a plate-glass maker necessarily a competent maker of optical glass.

In retrospect it is now evident that better progress would have been made, more glass produced, and much money saved had either a new optical glass plant been built or, for example, the plant of the Spencer Lens Co. been expanded rather than the attempt made to remodel an old plate-glass plant. Experience proved, furthermore, that in the manufacture of optical glass it is better to start with new hands than with plate or other glass makers, who are necessarily prejudiced and do not readily change their attitude of mind toward certain factory operations. The conservatism and inflexibility of the ordinary factory hand can be appreciated only through actual manufacturing experience.

It would seem to be a wise policy for the Government in time of war to concentrate its efforts on two plants for the manufacture of optical glass rather than on three or more. In two plants properly situated adequate quantities of optical glass can be produced to meet

all needs. In this connection, however, the increased destructiveness of airplane bombs and other demolition agencies should be considered. In case an existing glass plant is offered for conversion to the manufacture of optical glass, its adaptability for the purpose should be carefully considered before the conversion is sanctioned.

As a result chiefly of the efforts of the plants cited above, the actual manufacturing capacity for optical glass at the time of the signing of the armistice exceeded the total requirements of the Army and Navy planned for 1919. The quality of the glass was, moreover, steadily improving, and the inspection requirements were gradually made more exacting in order that, because of unsuitable optical glass, rejections in finished optics be reduced to a minimum.

In the early months of the war the production of optical glass had not reached a sufficiently secure basis to permit the placing of definite Government contracts for optical glass. In October, however, a contract was made by the Army Ordnance Department with the Bausch & Lomb Optical Co. for 3,500 pounds of different types of optical glass; by that time it was realized that the manufacture of optical glass was assured and that, although the consumption of optical glass by this plant itself was large, there would soon be a surplus of glass available for use by other optical instrument makers. The first deliveries on this contract were made in November, 1917.

At the time this contract was placed there were no Government inspectors available for the inspection of optical glass. Accordingly it was necessary to ascertain first the relative usefulness of the different methods available for the inspection of optical glass and to devise new methods in case the existing methods were found to be inadequate or otherwise unsuitable. A satisfactory routine for inspection was soon established and the first shipments of optical glass were inspected by the writer. Army Ordnance inspectors were then trained to the task and later Signal Corps and Navy inspectors. In order to expedite production and to establish inspection on a firm basis both Army and Navy inspectors were kept in close touch with the factory operations. They inspected large quantities of glass in process of manufacture before it had reached the stage for final inspection and acceptance. Although this practice was different from the established Government procedure of inspecting only the finished articles specified in the contracts, it was found in every instance to be beneficial both to manufacturer and to inspector because it led to a clear understanding of the significance of the specifications and of the steps essential to meet them satisfactorily.

In each Government contract for optical glass the tolerance limits for refractive index and ν-value were made as large as possible, about ± 0.002 in refractive index, n_D, for each type of glass. But in the early months of the war good melting pots were not available, and it

was difficult for the manufacturer to hold the melts of a given type even to these limits. The difficulty was overcome, in part at least, by shipping to a given manufacturer glass so selected from the different melts that the range of refractive indices was within certain tolerance limits. Unfortunately this plan was not followed consistently because of lack of proper care at the Army and Navy distributing centers; as a result, many manufacturers actually did receive shipments containing glass with much wider variations in refractive index than should have occurred; much time was thereby needlessly lost in changing and adapting tools to meet the relatively large fluctuations in refractive index. This situation arose because of a lack of appreciation on the part of certain Army and Navy officials of the optical glass requirements. The same lack of optical sense led one zealous officer to enter a glass plant before adequate inspection had been installed, and to order that a ton of glass, which had not been properly inspected, be sent to a manufacturer who was much in need of optical glass. The manufacturer in turn failed to inspect the plates before putting them into work with the final result that several thousand otherwise high-grade prisms had to be rejected because of faulty glass. This case is cited because it shows that the officer's action, commendable as it may have been in some respects, led only to disaster and waste of effort because the material with which he had to deal was optical glass and not simply glass or copper or zinc for which his order might have been justified.

War-time experience proved the need and value of trained personnel to organize and coordinate scientific and technical work; it proved the futility, as in the above case, of assigning any man or officer to a technical task for which he has no background of experience at least along similar lines. It demonstrated the necessity of centralizing among a competent few the task of handling the many factors which arise in connection with a technical matter such as optical glass and optical instruments. The records show that this plan was finally adopted with the result that in the latter part of 1918 the optical glass situation was well coordinated and well in hand.

Too strong emphasis can not be placed on the need for properly trained personnel to handle technical problems of this nature. In the last analysis personnel is the prime factor involved, and the nation which, during peace times, properly organizes and coordinates its scientific and technical forces so that they can be called upon in an emergency, has an immense advantage over a nation whose Army and Navy are out of touch with these forces. Proper cooperation between the civilian and military elements is essential in peace times if there is to be an effective working together during war times. Failure to appreciate this fact before the war cost this country much during the war and after. In highly technical lines, especially those

lines which have to do with engineering and scientific problems where special skill and experience are necessary, civilian experts are commonly in close touch with the details and are in a position to give good advice and aid. One of the chief difficulties encountered in the optical instrument situation during the war was the remedying of errors made by officials and officers who had been detailed to the job but who lacked knowledge of the problems and were in many instances a hindrance rather than a help.

This situation can be met only by a realization of the need for the adequate training of a selected few men in the Army along optical lines, not simply as users of optical instruments, such as range-finder and field battery observers, but also, as inspectors of optical instruments. It is equally essential that a certain number of civilians, who are well grounded in optical theory, be instructed during peace times in ordnance optical instruments, their field use, care, and inspection, so that in case of war these men may be ready, as a nucleus, to bear the burden of inspection and manufacturing supervision and to train others rapidly to become qualified inspectors. If a peace-time policy of this sort were followed civilian interest in these matters would be maintained with the result that in the event of war a potential organization of high efficiency would be available. War-time experience proved that men with a good working knowledge of optics soon became proficient inspectors and officers competent to handle optical matters; but that men, without this background of optical training, assigned as officers to optical instrument problems, proved incompetent and actually did more harm than good, stopping production here because of the arbitrary setting of tolerance standards which could not be met, and expediting production there which eventually proved to be useless because of the lack of proper tolerances and competent supervision. In retrospect these occurrences may be passed over with equanimity; but during the war they meant constant trouble and discouragement both for the manufacturer and for the field forces; nor did it increase the respect of the manufacturer to find the Army officer ignorant of the essentials of the technical subject to which he had been assigned and hence incompetent to deal with it intelligently and constructively.

On the other hand it was an inspiration to witness the zeal and ability with which a certain few officers of thorough grounding attacked and solved the problems; and particularly to see manufacturers lay aside other work in order to undertake the making of the military optical munitions needed by the field forces. It was this spirit of willingness to undertake a job and see it through, that carried the manufacturing program through to a successful end in spite of the lack of preparation and adequate training; but the cost of so doing and of learning by experience was excessively high.

Early in 1918 the requests for optical glass became so insistent from so many manufacturers that in March, 1918, a special section, called the military optical glass and instrument section, was created by the War Industries Board to handle the situation. Mr. George E. Chatillon, of New York, was appointed chairman of the section; Commander W. R. Van Auken and, later, Commander H. A. Orr, Navy representative, and the writer, Army representative. It soon became necessary, because of the very large demands of the Army and Navy for optical instruments for this section to take complete charge of the industry and, by a system of permissions, to supervise the entire output of all manufacturers of optical glass and of optical instruments.

Commercial orders were restricted to absolute necessities; requests for priority were passed upon. The optical glass, as produced, was controlled and distributed by this section to the several Governments departments and to manufacturers having direct Government orders. It was through this absolute control of the optical glass output that the entire optical industry could be so easily and effectively controlled.

Responsibility for the manufacture of the required quantities of optical glass was placed by the military optical glass and instrument section with the Director of the Geophysical Laboratory. Statistical reports were prepared weekly at the different plants showing the amounts of different types of optical glass ready for final inspection.

The requirements of the Army and Navy for optical instruments were carefully tabulated and their relative needs for optical glass were thereby ascertained. Allocations of optical glass were made with reference to these needs. This mode of operation of the section proved successful in every respect. The manufacturers, realizing the necessity for centralized control, entered into the plan whole-heartedly, accepted the rulings and requests of the section, and observed them conscientiously. The chief function of the War Industries Board was not to restrict industry but to direct it most effectively to work on munitions. How this was done is a familiar story in many other lines of industry and need not be repeated here.

Both the Army and Navy placed orders for optical instruments during the early months of the war, at a time before intimate contact with the armies in Europe had been established. With one or two exceptions these orders were placed with optical-instrument makers of established reputation who were in a position to produce the articles ordered, providing the necessary optical glass were made available. The orders, moreover, were for certain standard instruments, such as range finders, aiming circles, battery-commander telescopes, naval gun sights, field glasses, camera lenses, etc. These orders effectively covered the entire manufacturing capacity in this country for 1917 and for part of 1918. The policy of placing orders with firms of recognized standing and, in case an inexperienced firm

solicited a contract, of awarding a part only of the required number to the new firm and the remainder to an old firm, proved to be a wise policy. The old firms proceeded to fill the contracts and in time delivered the instruments; many of the new firms required assistance, and in this connection the War Industries Board aided materially.

By the end of 1917 requests for many new types of instruments, which the European armies had found useful in the field, began to flow in from the American Expeditionary Forces; the optical industry was then confronted with the situation that its available capacity had already been bespoken for some months to come. The result was an energetic appeal from the several departments of the Army and Navy to each manufacturer to accept more orders, each department considering only its own needs. Careful search was made for manufacturers who might be persuaded to undertake optical work. By February, 1918, the general confusion which existed because of the many diverse, noncoordinated agencies at work led to the realiztion of the need for centralized control and in a short time furnished additional reasons for the formation of an optical section on the War Industries Board. Much credit is due Mr. Chatillon, chairman of this section, for his effective treatment of the situation and the organization and coordination of the many factors involved.

In April, 1918, an army commodity committee on optical glass and optical instruments was formed with the Army representative on the optical section of the War Industries Board as chairman, for the purpose of coordinating the Army needs for optical instruments. This committee functioned under the Director of Purchases and Supplies. It held monthly meetings and served to bring together the Army officers directly concerned with optical munitions. One of the results of the efforts of the Director of Purchases and Supplies was the consolidation, in the Ordnance Department, of the procurement of all optical munitions for the Army with the exception of a few special instruments. Strenuous objection to the consolidation was made at first by certain Army departments on the plea that special knowledge was required to purchase the optical instruments required by them; but the results of this consolidation proved that the fears thus expressed were groundless, partly because the officer, Lieut. M. P. Anderson, in the Ordnance Department, directly responsible for the procurement of optical munitions, was thoroughly trained to the task and was experienced in optical matters.

From April to August, 1918, an earnest effort was made by the War Industries Board, the Army, and the Navy to interest manufacturers who might undertake the production of optical munitions. The result was that many firms, who had never done work of this kind, patriotically accepted contracts for instruments or optical or

mechanical parts, and at the time of the signing of the armistice were beginning to produce satisfactorily. In general the policy was followed to let contracts for instruments of high precision to experienced firms and to reserve the simple types of instruments for the less experienced makers.

As a further incentive to expedite production, the Ordnance Department established a training school for lens and prism operatives at Rochester, N. Y. It was felt that, were the opportunity offered, many young women might engage to do work of this kind during the war period. At the Rochester school a number of operatives were thus trained, but the results were not altogether satisfactory, chiefly because of a lack of real interest and support on the part of the large optical manufacturers in Rochester. A school of this nature to be successful requires the enthusiasm and interest of good teachers, and these evidently could not be spared by the manufacturers.

A second, more successful school was established at Pasadena, Calif., for the training of expert grinders and polishers for precision optics, chiefly roof-angle prisms. This school was operated in connection with the optical shop of the Mount Wilson Observatory of the Carnegie Institution of Washington. Credit is due to Mr. G. W. Ritchey for his efficient operation of this school and shop.

The optical industry during the war proved equal to the emergency and in November, 1918, was rapidly approaching the peak value of deliveries. Production and deliveries were proceeding on an immense scale. By this time the industry had been well organized and coordinated. New additions had been made to old factories, new factories had been erected and a manufacturing capacity for optical instruments adequate to supply the needs of both the Army and Navy for 1919 was available. This condition had been practically attained by September, 1918, so that the optical section of the War Industries Board was able to devote part of its time to the question of design of optical instruments with a view toward simplification and standardization. Many of the instruments in course of manufacture were direct copies of European instruments, and manufacturers complained because the designs had not been made with reference to American methods of quantity production. In many instruments a great saving both in time and expense could have been effected by appropriate changes in design without affecting in the least the field performance of the instrument; but to accomplish this properly requires time and much consultation. Under the circumstances, it was decided best to go ahead with the production of usable designs, even if they were direct copies of European instruments and thus to insure the desired output. As soon as adequate production had been estab-

lished, steps could be, and actually were, taken to improve and to standardize the designs of many of the instruments.

With the signing of the armistice the need for further production ceased. Many contracts were canceled outright and appropriate settlements were made; other contracts were canceled in part, and still others were allowed to continue to completion. Manufacturers, who had engaged in optical work as a patriotic duty only, returned to their normal peace-time activities. The optical instrument manufacturers themselves were soon deluged with commercial orders, because of the release of all restrictions and control of the industry by the War Industries Board on November 16, 1918. Thus the transition from war-time to peace-time activities was begun.

After the Civil War there was no corresponding adjustment of the optical industry. The total value of orders for optical apparatus during the Civil War was almost negligible. During the recent war, the total value of Army and Navy orders for optical munitions was over $65,000,000, of which about $50,000,000 was for the Army. What it may be in another war a century, or even some decades hence, no one can tell; but, if the lessons of the recent war have not been entirely forgotten this country will be in a better position to produce the necessary optical munitions than it was in April, 1917. The purpose of the present report will have been accomplished if a small part of the experience gained in the recent war in the production of fire-control and other optical apparatus is not entirely lost, but is available for use in an emergency.

In the manufacture of optical glass it was fortunate for this country that war was not declared in the first decade of this century rather than in the second. In 1905 little was known of the chemistry of silicates at high temperatures and there was then no adequate personnel available for the task. The records show that during the recent war we received no assistance, either direct or indirect, from other countries in the solution of the problems of optical glass manufacture. The details of optical glass manufacture were held secret in all European countries and were not to be divulged, even under the stress of war-time needs. Fortunately, it proved possible for us to make good optical glass without the knowledge of these secrets, which, in point of fact, may prove to be double-edged and serve to impede progress and to be an actual hinderance rather than an aid to a manufacturer if he holds them in too high esteem. This would no doubt have been equally true in 1905. Although large quantities of optical glass are not needed, optical glass is an essential part of all instruments of observation. The optical glass industry is, therefore, a singularly important key industry, the control of which means control over a whole series of industries and of research and technical laboratories and institutions. It was probably for this

reason that we were unable to secure any information regarding its manufacture from other countries.

It was fortunate for us that before this country entered the war certain manufacturers had realized the need for optical glass and had erected optical glass plants of satisfactory design. They had, moreover, produced some optical glass of fair quality and had accumulated a good foundation of experience on which it was possible to build. This would not have been the case in 1905. It was also fortunate that there existed at the beginning of the war a scientific research laboratory with a personnel experienced, not in the manufacture of optical glass, but in the fundamental principles underlying its manufacture. The resources of this laboratory were offered to the Government in the emergency; the offer was accepted and the problem of optical-glass manufacture was attacked as would any similar research problem have been attacked. The research investigator is constantly facing new and unexpected problems in his own work, and, as a result, develops resourcefulness and adaptability as well as the faculty of proceeding directly to the essentials of a problem. Shortly after the work was entered upon the more important defects of the existing practice were discerned by the scientists and appropriate remedies were devised to overcome them.

It is only just to admit that in addition to the many other elements essential for the production of optical glass in this country we were favored by good fortune and made the best of it. If a future emergency should arise it can hardly be expected that a laboratory of similar experience will be available or that the manufacturers will have builded so wisely beforehand. It is therefore a wise policy for the Government to encourage the manufacture of optical glass in this country by placing orders, during peace times, for optical glass with the manufacturers, thereby building up a reserve stock of good glass against a possible emergency. This policy is being followed by certain other countries. In the case of optical instruments similar arguments are valid; but the fact that new instruments are being devised constantly makes it inadvisable to store large stocks of these instruments. The maintenance of optical repair and manufacturing plants by the Army and Navy is a wise provision, because these function primarily as training schools for personnel against the hour of need.

In view of the highly technical nature of optical instruments both in design, production, and repair it is desirable that a single optical plant with competent personnel serve the entire Army. It is not feasible and would be unwise for the different departments of the Army each to maintain separate optical shops or even separate sections for the design only of optical instruments. The argument has been advanced that in any given branch of the service only the

members of that service have adequate knowledge of the field conditions under which it operates and that, therefore, they alone are competent to design the apparatus needed. This is, no doubt, true for much of the material required, but in the case of optical instruments special conditions exist which render this plan unworkable. Optical engineers of experience are scarce and unwilling to spend their entire time on the few problems offered by any single branch of the service. The particular problems, moreover, which any Army department considers peculiar to itself have much in common with those of other departments; and for each department to maintain a separate section for the design of optical instruments would mean serious and inefficient duplication of work with consequent waste of time and of public money.

The fact that both in war time and in peace time the Ordnance Department is responsible for the bulk of the Army optical work and has built up a satisfactory optical shop at Frankford Arsenal with competent personnel indicates that all Army optical work should be done there; also that Frankford Arsenal should be made responsible for the design and production of all experimental optical instruments suggested to meet any new conditions which may arise. The special knowledge of the conditions under which the proposed new instrument is to function can be given by officers or civilians of the special branch of the service which is to use the instrument; but the design of the instrument to satisfy these conditions and to be at the same time a manufacturing possibility should be made at Frankford Arsenal as the logical optical organization within the Army. It is imperative that the Army and the Navy each maintain an optical plant not only for the design and test, production, and repair of military instruments, but also for the training of personnel along these lines. It is for this reason especially that no other department of the Government can function satisfactorily for the Army and Navy in this respect, and that the Army and Navy optical shops can not well be consolidated into one large shop.

WAR DEPARTMENT,
OFFICE OF THE CHIEF OF ORDNANCE,
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